Methodology for the Application of the IMO Polar Code to Vessels Operating in Antarctic Waters

by

Mohamed Daboos, MSc (Marine Engineering), BTech (Marine Engineering)

National Centre for Maritime Engineering and Hydrodynamics
Australian Maritime College

Submitted in fulfilment of the requirements for the degree of Master of Philosophy
University of Tasmania

April 2021

Declarations

Authority of Access

This thesis may be made available for loan and limited copying and communication in accordance with the *Copyright Act 1968*.

Declaration of Originality

This thesis contains no material accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis. To the best of my knowledge and belief, no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Date: 26 April 2021

Signed:

Mohamed Daboos

Abstract

The Antarctic and the Southern Ocean region are well known for environmental fragility and harshness, which may pose unprecedented risks to shipping traffic. However, novel and innovative technologies continue to prepare vessels better than ever to cope with harsh polar conditions. The Antarctic and the Southern Ocean are also coupled with the abundance of marine resources and possibilities for economic activity, which has led to considerable international attention and the implementation of rules and guidelines in an effort to conserve and protect both human life and the polar ecosystem. Most prominent amongst these is the International Code for Ships Operating in Polar Waters, adopted by the International Maritime Organisation (IMO), in order to better regulate the operation of vessels within the Antarctic region.

This thesis considers the winterisation process of the MV-Bluefin's, a research vessel, in the context of the vital seawater (SW) cooling system, which transfers waste heat away from the operating systems to better assist the vessel in withstanding the harsh climatic conditions. Calculated for a grid of two-dimensional weather vectors - SW temperature as the first coordinate and air temperature as the second - the MV-Bluefin's power demand may exceed the generators' available power supply as a direct result of the extreme temperature fluctuations. The aforementioned failure probability is added to the vessel's standard failure risk.

Two models have been developed as part of this thesis for assessing such risk. The first model distributes the extreme weather vector according to a truncated bi-normal distribution. The power risk is analytically derived as the integration of the probability density function (PDF) over the critical region, identified as the weather vector area where the power failure is expected to occur. Conversely, the second model divides the vessel's mission into an arbitrary number of segments. Each segment consists of several days with the daily weather vector distributed according to a segmented truncated bi-normal distribution. Thus, the power risk is derived through a computer simulation of 10,000 pseudo-missions and is only considered successful if all weather vectors fall outside the critical region.

The power risk is calculated for both models as a function of ambient temperatures. It estimates the level of risk according to the specific vessel dynamics, human factors within a confined space, and a variety of operational and environmental factors, thus providing an early warning for vessel operators and being used to assist in real-time decisions throughout vessel missions. In the case of the MV-Bluefin, the simulation observed the probability of the system indicating a warning which increased concurrently with the likelihood of the vessel experiencing a power risk, thus allowing for appropriate preventative and mitigative measures to be taken.

Acknowledgements

Peace be upon you all. I would like to thank the Almighty God for giving me the time and the strength and enabling me to complete this work.

I have had three excellent navigators, Associate Professor Michael Woodward, Professor Kiril Tenekedjiev and Dr Christopher Chin, at the Australian Maritime College to help me on this collision-free journey. A special thanks to my primary supervisor, Associate Professor Michael Woodward, for the opportunity to conduct this research and for all his inspiration, support and guidance. I would like to express my sincere thanks to Professor Kiril Tenekedjiev from NCMEH for his advice and excellent guidance. I also thank Dr Christopher Chin for working with me on every step of my research through his kind support and encouragement.

Thanks to my colleagues at the AMC, friends and family for invaluable help and support. Special thanks to Professor Nataliya Nikolova, Dr Nagi Abdussamie and Dr Al-Amin Baksh for several inspiring discussions and suggestions.

Last but not least, I would like to express my heartfelt gratitude to my beloved family, who has been supporting and encouraging me all the time.

The National Centre for Maritime Engineering and Hydrodynamics (NCMEH) of Australian Maritime College (AMC) financially supported this research project, and this support is gratefully acknowledged. I also thank the Graduate Research at the University of Tasmania for their financial and relevant support.

Table of Contents

List of Figures

List of Tables

Nomenclature

Area	Metres Squared	[m^2]
Deadweight	Tonne	[t]
Different Temperatures	ΔT_M	[$^{\circ}C$]
Distance	Metres	[m]
Horsepower		[hp]
Mass Flow Rate of Coolant	Kilogram per Second	[kgs^{-1}]
Motor Efficiency		[η_m]
Motor Power		[W]
Overall Heat Transfer Coefficient	Watts per Square Metre Kelvin	[$W/(m^2K)$]
Power	Kilowatt	[kW]
Pump Efficiency		[η_p]
Revolutions per Minute		[rpm]
Salinity	Parts per Thousand	[t/m]
Shaft Power		[W]
Speed	Knots	[kn]
Specific Heat Capacity	Joule per Kilogram Kelvin	[$J\ kg^{-1}\ K^{-1}$]

Abbreviations

ABS	American Bureau of Shipping
ARV	Antarctic Research Vessel
ATCM	Antarctic Treaty Consultative Meetings
ATCP	Antarctic Treaty Consultative Party
ATS	Antarctic Treaty System
BANZARE	British, Australian, New Zealand Research Expeditions
CCAMLR	Convention of the Conservation of Antarctic Marine Living Resources
CBM	Condition-Based Maintenance
CP	Centrifugal Pump
EMSA	European Maritime Safety Agency
FSC	Flag State Control
FW	Freshwater system
IAATO	International Association of Antarctica Tour Operators
IACS	International Association of Classification Societies
IMO	International Maritime Organisation
USCGC	United States Coast Guard Cutter
HSC	High Sea Chest
LOS	Lubrication Oil System
LSC	Low Sea Chest
LTFWCL	Low-Temperature Freshwater Cooler
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MRCC	Maritime Rescue Co-ordination Centre
MSC	Maritime Safety Committee
PoF	Probability of Failure
RCC	Rescue Coordination Centres
SAR	Search and Rescue
SARS	Search and Rescue Service
SCPP	Sea Cooling Pump
SOLAS	International Convention for the Safety of Life at Sea
SS	Sewage System
STCW	International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers
SW	Seawater
SWCCS	Seawater Central Cooling System
SWCCSC	Seawater Central Cooling System Chest
SWCIS	Seawater Cooling Intake System
SWCS	Seawater Cooling System
SWCSM	Seawater Cooling System Modification

Chapter 1: Introduction

1.1 Background

The operation of vessels in and around the Antarctic and Arctic regions has always been a matter of concern for the International Maritime Organization (IMO) as a result of harsh and inhospitable weather conditions, a distinct lack of infrastructure, remoteness and isolation from land, darkness and the distinct lack of accurate charts relative to other areas of the globe, as well as the challenges presented by communication systems and other navigational aids. The aforementioned challenges increase the risks involved in Search and Rescue (SAR) and make clean-up operations demanding and expensive. The hostile weather conditions and reduced air temperatures have been seen to decrease the effectiveness of a number of vessel components, including deck machinery and equipment required in emergency scenarios. The presence of ice poses a unique obstacle in that it may impose additional loads on the vessel as a whole, especially on the hull and propulsion system.

Despite the risks, the demand for resources and tourism has presented a unique market for the merchant, cruise and offshore vessels to operate in polar regions. Maritime transportation has revolutionised inter-continental trade and overseas tourism industries. Regulated by the International Convention for the Safety of Life at Sea (SOLAS) [1] and the International Convention for the Prevention of Pollution from Ships (MARPOL) [2], vessels operating in international waterways and the high seas still face a significant threat of accidents and injuries. Although several regional and international bodies control shipping operations, there are many accidents reported annually, which is valid for vessels operating in the polar and sub-polar regions, as they are more prone to accidental loss or emergency due to extreme weather conditions. To mitigate such accidents, a number of regulatory authorities have introduced guidelines and amendments aimed at shipping practices in certain geographical areas. An example of this is the polar code that aims to regulate vessels moving through the ice-covered regions of the Arctic and Antarctica. The Arctic council’s annual report identifies shipping related accidents and their causes, in addition to a discussion on the prospects of shipping in the region and its brief history.

1.2 Research Gap

The research gap identified by this work are:

1. The number of accidents involving vessels traversing through the Antarctic region is not well documented, despite causing human casualties in some cases; the research into polar vessel safety is limited.
2. The harsh environment of the Antarctic region is not yet quantified.
3. The lack of public-domain data presents a key challenge in compiling a comprehensive Quantitative Risk Assessment (QRA) into polar vessel operations' safety.
4. Performing a complete QRA study for ship safety and operations in Antarctica remains challenging due to a lack of data in the public domain.
5. Considerable uncertainty still exists when engaging experts in the development of QRAs.

1.3 Research Questions

The research questions answered by this work are:

1. How can a rational method of identifying critical vessel systems be developed better to understand winterisation requirements and at what level?
2. How can a power risk model (as proposed in Q1) apply to external and internal factors that may affect a polar vessel?
3. How to identify the crucial systems' safety performance indicators onboard a polar vessel and calculate power failure probability?
4. What are the implications and limitations of applying the sixth chapter of the polar code, namely machinery installations, to vessel systems?

1.4 Aims and Objectives

This thesis investigates the research questions in Section 1.3 to develop a numerical model that may help crew members identify power failure indicators early to avoid casualty in the harsh Antarctic environment. This model may also assist in providing recommendations for the level of winterisation required for crucial systems by determining the vessel's ability to cope with frigid seawater (SW) and air temperatures. Finally, the findings will be applied to the Australian Maritime College's flagship research and training vessel, the MV-Bluefin, to understand better the limitations posed by the inhospitable polar regions.

As shown in Figure 1, the flow chart demonstrates the relationship between this thesis's objectives and all the tasks associated with producing this research.

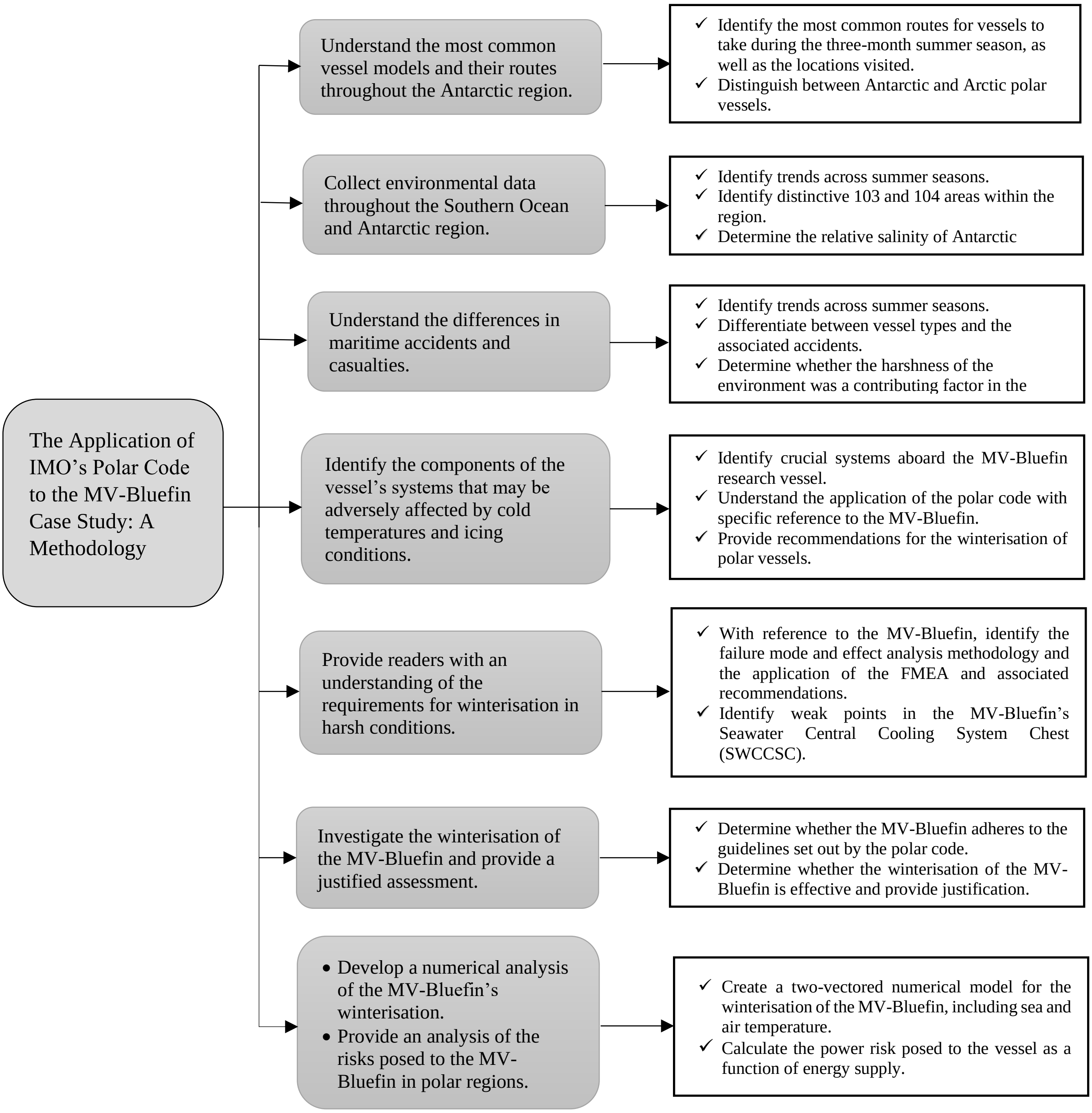

Figure 1: Thesis objectives and associated tasks.

1.6 Methodology

This thesis will evaluate the additional risk of winterisation in the Antarctic regions in the form of a risk analysis, calculated on a two-dimensional weather vector grid where the first coordinate relates to SW temperature. The second relates to ambient air temperature, which is calculated as an addition to the MV-Bluefin's standard failure risk. The probability of power failure is denoted as power risk, which would be modelled using MATLAB.

The first model distributed extreme weather vectors according to a truncated bi-normal distribution. The power risk is analytically derived as the integration of the truncated bi-normal PDF over the critical region, denoted as the weather vector region where power failure will occur. The second model divided the vessel's route into an arbitrary number of segments, where each segment consists of several days with the daily weather vector distributed according to a segment truncated bi-normal distribution. The power risk is derived using a computer simulation of 10,000 pseudo-missions. A pseudo-mission consists of daily weather vectors being randomly generated according to the known specific segment truncated bi-normal distributions. The mission is considered a success if all the weather vectors are outside the critical region. For both models, the power risk is calculated as a function of the provided energy supply. Power risk is calculated of the mission with the same parameters as the one described at the end of section 8.4. The $Risk_{model3}$ was 0.3703. The output of the software is shown under the function in Appendix D. The power risk for each of the segments is given in Appendix D after the function. As evident, the third power risk model results practically coincide with those from the second power risk model. However, the function `Risk_simulate_eval_dist.m`. with 10000 pseudo realities calculated the results for 8.37 seconds, while the `Risk_generalized_model.m`. calculated the results for 0.074 seconds, which is more than 100 times faster.

Using the second and third power models, which can be calculated the mission power risks for several different values of the hypothetical power supply. In that way, we can obtain the mission power risk as a function of the hypothetical power supply, which is useful to determine the investment in a separate mission.

To estimate the probability of power risk, the models consider a wide range of factors, including vessel dynamics, operational and environmental factors, and human factors, and is, therefore, able to provide an early warning. As such, the proposed methodology may assist in real-time decision-making and allow for appropriate preventative measures to enhance the vessel's safety and operations.

Chapter 2 will review the International Association of Antarctica Tour Operators (IAATO) [3], an organisation founded by private-sector operators to promote ecologically sustainable and environmentally responsible tourism in the Antarctic region. This review was done in light of the legislation set out by the Antarctica Treaty System (ATS) [4], the IMO and POLAR VIEW (which is a chapter of the Polar code) [5-9], and the International Association of Classification Societies (IACS) [10, 11].

Chapter 3 will review the literature, published statistical data, and reported accidents to determine the number of accidents and the type of accidents occurring, the vessel most likely to be involved in an accident, as well as any casualties resulting in such accidents.

Chapter 4 will review the operations, routes, and winterisation of a variety of polar vessels in the Antarctic region and the frequency and duration of their missions in an effort to assist vessels in transit through the harsh Southern Ocean.

Chapter 5 will critique IMO's polar code, which regulates the operation of vessels in polar regions. The two stages considered by this thesis are those that identify the critical components that are negatively affected by low temperatures and icing conditions and the subsequent drafting and implementation of guidelines and the application of safety functions and techniques for both machinery space and auxiliary machinery.

Chapter 6 will provide an overview of the MV-Bluefin's capacity to transport passengers, operate in polar regions, demonstrate the heat tracing and insulation system, preserve or increase the pipes' temperature. This was performed to evaluate the various winterisation systems best onboard the vessel and ensure compliance with the polar code.

Chapter 7 will evaluate the power requirements of the MV-Bluefin to safeguard against system failure in the face of hostile polar temperatures and identify potentially vulnerable systems. This chapter develops an innovative numerical model to classify the effects of harsh temperatures on various systems.

Chapter 8 will evaluate the additional risk of winterisation in the Antarctic regions in the form of a risk analysis, calculated on a two-dimensional weather vector grid where the first coordinate relates to SW temperature. The second coordinate relates to ambient air temperature. It was calculated as an addition to the MV-Bluefin's standard failure risk; the probability of power failure is denoted as power risk, modelled in MATLAB.

1.7 Novelty and Contribution

This study includes the following novelties:

- No model has previously been developed to estimate the risk power demand and the probability of failure (PoF) for MV-Bluefin research vessel systems winterising in low air temperature in the Antarctic.
- No previous model has been able to predict the probability of such power failure, which is additional to the standard failure risk of the MV-Bluefin vessel and update the results in real-time for ship systems operating in the Antarctic.
- Previously, there was no methodology or techniques that could calculate risk power for a grid of two-dimensional weather vectors (first coordinate SW temperature and second coordinate air temperature) for winterisation of MV-Bluefin vessel systems to operate in the Antarctic regions.

Chapter 2: The International Association of Antarctica Tour Operators (IAATO) and the Operation of Vessels in Antarctica

2.1 Introduction

When considering the risks facing vessels traversing the Antarctic region, weather and temperature-related hazards can be named. However, several lesser-known risks exist mostly in the form of an increasing number of vessels in the region leading to higher traffic, continental shelf creating subsurface hazards, sea-ice cover decline, navigation through previously uncharted regions, and the growing presence of tourists.

To mitigate the effects of such risks, the IMO adopted the polar code for marine vessels operating in polar waters [6], which entered into force on the first of January 2017. The effectiveness of the code was seen when a number of amendments mandated its use under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [12], as well as under the SOLAS [1] and MARPOL [13].

The implementation of the polar code, along with support from POLAR VIEW [5-9], the IAATO [3], and the IACS [14] has driven continued support for the work of vessel operators, as well as for the development of tools which can assist in implementing the requirements of the code effectively, including an ice and temperature database and Risk Index Systems [15]. This chapter aims to review IAATO's regulation of permanent tourist facilities in the Antarctic region and legislation set out by the ATS [4].

The objectives that can be achieved are:

- The identification of ATS legislation which currently regulates all activities conducted below 60°S;
- The review of POLAR VIEW, as well as IACS and IAATO; and
- IAATO undertakes the SAR exercise evaluation with the Maritime Rescue Co-ordination Centre (MRCC) based in Buenos Aires, Argentina. This was conducted to mitigate the distinct lack of infrastructure in regions where the polar code is highly applicable.

Founded in 1991, the IAATO regulates permanent tourist facilities in the Antarctic region to promote safe and environmentally responsible practices in the private sector. Coupled with the legislation set out by the ATS, all regulated activities, including that of tourism operators, conducted below 60°S, are prohibited from any military action or other, more obscure operations. Furthermore, tourist activities are not prohibited under the Madrid Protocol, as they are classified as non-governmental activities.

Developed under IAATO, the original guidelines regarding visitors and tour operators formed the basis of Recommendation XVIII-1 of the ATS, which provides guidance for visitors and non-governmental tour organisers to the region, and assisted in developing the high standards and best practises which aim to protect the fragile Antarctic environment. Furthermore, IAATO has been represented at the Antarctic Treaty Consultative Meetings (ATCMs) and presents an overview of the annual tourist activities and associated statistics, all of which can be found on IAATO's website.

2.2 Search and Rescue Operations in Antarctic Waters

Subsequent to the SAR development, IMO divided the Antarctic region into five distinct maritime regions—Argentina, Australia, Chile, New Zealand and South Africa—all of which are managed through seven Rescue Coordination Centres (RCC) [8, 15]. This aims to promote the safety of vessels operating in Antarctic waters regarding all activities being undertaken. As a result, safety has played a vital role in the discussions of the ATCM since 1961. While human activity in the Antarctic is expected to increase in fishing, national program operations, shipping and tourism, so too will the challenges and risks associated with SAR operations in the Antarctic and Southern Ocean region. As a result, discussions regarding the SAR facilities, procedures, and contingency plans can be improved upon in the Antarctic [8].

In an effort to increase the success and effectiveness of SAR operations in the Southern Ocean and Antarctic region, the ATCM adopted Resolution 4 (2013). It was recommended that all Antarctic Treaty parties commit to sharing their best SAR practices related to SAR and improve their international cooperation in an effort to promote effective implementation of SAR protocols that would prove to be beneficial in the context of the Antarctic region. It was further recommended that all parties support COMNAP [16].

Operational guidelines for polar vessels dictate that the ship should only be operated within the intended weather conditions and all design limitations. These guidelines mentioned also apply for all passenger ships operating in polar waters, including tourist's vessels, as well as taking into account the distance between the vessel and the closest SAR facilities, outlined as part of the "Enhanced contingency planning guidance for passenger ships operating in areas remote from SAR facilities" (2006, MSC.1/Circ.1184) [8].

The entry into force of the polar code marked a historic milestone in the work of the IMO to protect both the seafarers and the passengers aboard marine vessels in the harsh and volatile polar environments surrounding Antarctica and the Arctic, respectively, as well as preserving the ecosystems themselves [17, 18]. This chapter provides an overview of the code, including the requirements and provisions regarding maritime safety and marine environment protection and the Antarctic Treaty Consultative Party (ATCPs) decision to develop guidelines regarding Antarctic shipping and related activities.

Despite an ATCP meeting in 2000, where a panel of Antarctic treaty experts was consulted [19] on developing and implementing Antarctic guidelines was slow. Improvement was eventually made when the 2004 ATCM moved forward with new recommendations for ships operating in the Arctic and Antarctic regions' ice-covered waters and aiming to amend the IMO Arctic guidelines with the new guidelines [18]. However, significant changes to the IMO guidelines regarding both the Arctic and Antarctic regions occurred between 2008 and December 2009 [20], with all amendments entering into force from 1 January 2011 [19]. The mandated training and certification for officers and crews serving on polar vessels under the STCW have also been described in this chapter. This chapter concludes by examining and discussing further measures that could be taken to ensure the safety of polar shipping, taking into consideration the ongoing discussions being held at the IMO.

2.3 Overview of Polar Waters

The difference between the two poles is illustrated in Figure 2, which can be made in that the Arctic, or the North Pole, is a frozen ocean surrounded by continents. Simultaneously, the Antarctic, or the South Pole, is a frozen continent surrounded by oceanic waters. Due to the harsh climate and weather conditions, both polar regions face extreme isolation from the rest of the world, which results in an ecosystem and environment that is vulnerable to external influences and susceptible to negative impacts, particularly human activity. As such, the polar code aims to ensure that vessels' operation within the environmental conditions is safe, sustainable, and has minimal impact. However, the cruise and tourist industries may benefit from the warmer temperatures caused by climate change, where polar waters become less hazardous due to a lack of floating ice packs. Perhaps this part of shipping has been the least affected by the last few years' financial and economic turmoil.

Only vessels that intend to operate within the Arctic and Antarctic areas defined in the polar code must comply [21]:

- Arctic: Generally, north of 60°, and limited by a line from Greenland; South at 58° north of Iceland, southern shore of Jan Mayen - Bjørnøya - Cap Kanin Nos.
- Antarctica: South of 60°. The polar code's safety part applies to ships certified under SOLAS, i.e. cargo ships of 500 GT or more and all passenger ships.

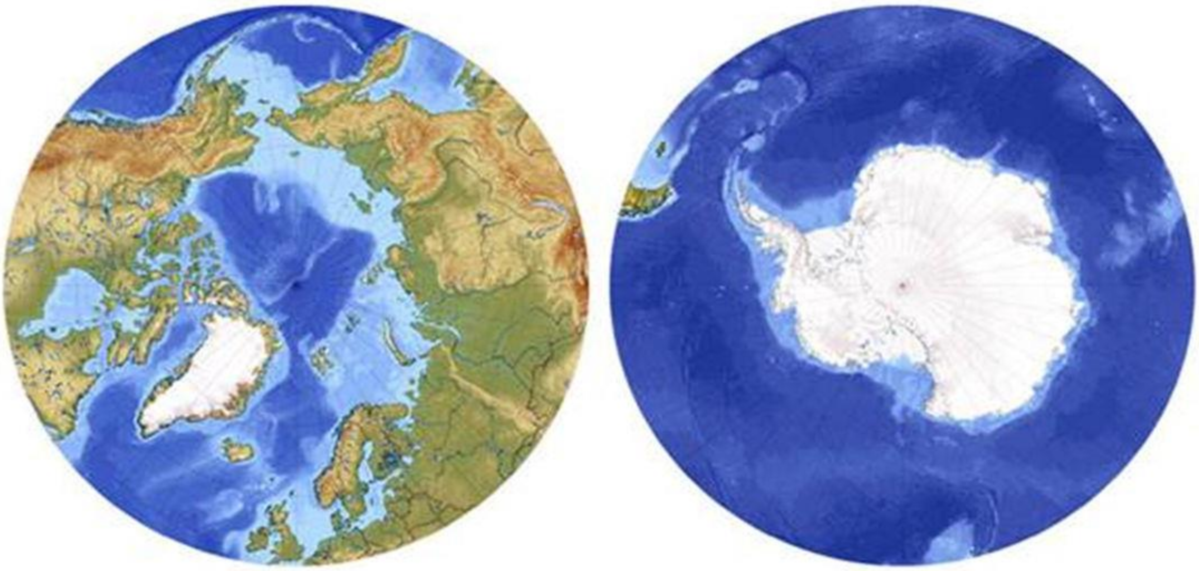

Figure 2: Maximum extent of the Arctic (left) and Antarctic (right) waters [22].

As a result of the Arctic containing vast oil reservoirs and the Antarctic being rich in various other resources, rapid growth is expected in several industries, including transit shipping, oil and gas industries, and producing oil gas transport by type of ship. However, this expansion in production and extraction will result in increased emissions. Unfortunately, the substitute for oil as a transportation fuel is difficult to find, and massive gas resources are more climate-benign than coal. Arctic resources, specifically crude oil, are dispersed unequally throughout the region, which is predicted to play a growing role in the global economy. However, rapid growth in oil and gas transportation has resulted in increased emissions released into the atmosphere [23]. As resource accessibility becomes more effortless, new challenges emerge for accident response, polar engineering, extraction and harvesting, SAR, transport [24], and planning and prediction difficulties resulting from weather changes and global warming. As a result of the aforementioned challenges and high costs associated with hazardous weather conditions, Arctic oil and gas production's prospects remain unclear [19, 23].

However, Ice-strengthened vessels require that all machinery installations provide functionality under hostile environmental conditions and consider loads imposed directly by ice interaction. The polar code also dictates that machinery installations and associated equipment must be protected against the aforementioned effects. For more details, see chapter 6 of Marine Environment Protection Committee (MEPC) 68/21/Add.1Annex 10. Further chapters relating to the risk posed to the environment by vessel operations, as well as the risk posed to vessel operations by extreme environmental hazards, will be developed by Det Norske Veritas (DNV), including the ban of heavy fuel oil, which has been introduced in the Antarctic region [5, 25].

Tourist activities in the form of cruise vessels predominantly occur in the ice-free waters of the Arctic summer season, the heaviest traffic occurring around Iceland, the western Greenland coast, Northern Norway, and Svalbard. The ice-covered waters of the region are hazardous, and as such, the only cruise-like activity that takes place during the winter months is the Russian nuclear icebreaker trips between Murmansk and Franz Josef's Land, which has been occurring since the 1990s.

While considered a niche and specialist market, the Arctic cruise industry is fast-growing, with big cruise operators undertaking sailing activities to the edge of Greenland and Svalbard ice borders [26]. While complete Arctic cruise data is challenging to obtain, indications of future development can be seen in Danish and Svalbard data [26], including the construction of passenger ship facilities in the Danish seaports of Greenland, leading to a 48.9% increase in the number of cruise ship arrivals between 2005 and 2008 [26].

The Arctic sees a variety of vessels in operation in the northern ocean each year, including icebreakers which are used to access the extreme north, research vessels that are often refurbished to reflect cruise ship comforts, a number of ice-class vessels, ice-strengthened vessels, as well as ships with ice capability. Very few purpose-built ice-strengthened cruise liners operate in the Arctic; however, a massive number is being used in the Antarctic and the Southern Ocean regions. The harsh winter climate in the Arctic drives polar cruise liners to the south for the Antarctic summer and vice versa. As a result of the extreme isolation, cruise vessels operating in the polar regions act as very much self-contained units, independent of land infrastructure. When everything works smoothly, this arrangement suits all stakeholders except offers little protection to the cruise ship operators, crew, and passengers in an accident or emergency. As a result, coastal states face extreme challenges in providing adequate search and rescue service (SARS) to Arctic cruise activities. The polar code aims to reduce the risks above in the Arctic and Antarctic environments. The likelihood of survival in the polar regions after an accident or disaster is, according to the polar code, influenced by one of two factors:

Environmental Exposure – The human body is highly vulnerable to low air and water temperatures, exposure to which can result in either [15]:

- Hypothermia – A reduction in overall core body temperature, as indicated by shivering, ultimately results in a loss of cognitive abilities and, in extreme cases, death.
- The freezing of bodily appendages – When experiencing extremely low temperatures, frostbite can occur after mere minutes of exposure. As a result of the affected limb's reduced functionality, the probability of survival is again diminished.

Compared to temperate, or even tropical, regions, an individual's survival time exposed to sub-zero temperatures is drastically reduced. Several other distinct features are present in the Arctic and Antarctic environments, respectively, which represents additional challenges for individuals who may need to abandon the ship in case of emergency, including ice and icebergs, as well as hostile wildlife.

The IAATO took a SAR exercise with MRCC Argentina in March 2018 and attended the third annual for Antarctica /Arctic for the SAR Workshop/tabletop exercise in Iceland in April 2018. These initiatives are essential in building relationships, trust and understanding for the SAR [3].

Rescue Timeframe – As a result of the lack of infrastructure in the regions where the polar code is most applicable, the time taken for SAR to take place is unquestionably long. Most SAR operations rely on helicopter evacuation; however, limitations of this method include both the highly volatile polar weather and the more critical restricted range and capacity to transport survivors. As a result of the limited helicopter range, most polar code areas are inaccessible. In helicopter-accessible regions, typically only 10 to 20 persons can be taken aboard at any one time [27].

In case of any marine accidents where the number of casualties is substantial, rescuer access to the site is essential. However, the vast distances that the vessels are required to cover coupled with relatively low vessel concentrations has resulted in a substantial amount of time necessary for a SAR operation to occur [28], as shown in Figure 3.

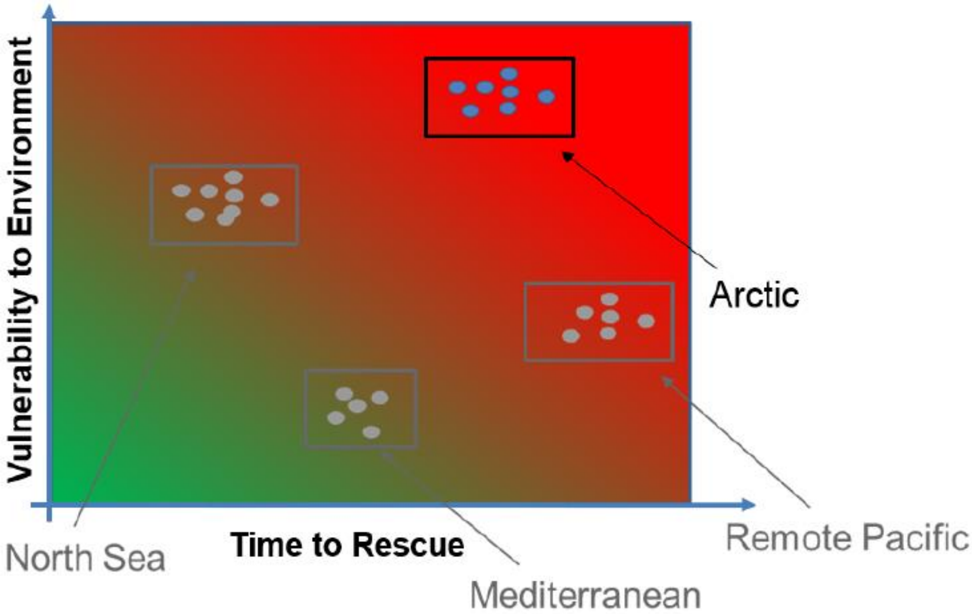

Figure 3: Rescue timeframe as a function of human vulnerability in the polar environment [28].

The combination of the factors, as mentioned, presents unique and significant challenges to human survival in regions where the polar code is applicable. While considering human vulnerability to harsh climates and distances between rescuers and accidents, a significant discrepancy exists when comparing the mean number of accidents taking place in polar regions and more temperate parts of the world, resulting in a significant forecast lessening survival time. This can be prevented in part by polar vessels being self-sufficient, where lifesaving equipment, personal and group protective equipment, and appliances are carried onboard, thereby providing adequate protection. This applies to all marine ships operating in polar waters, including rescue craft [27].

2.4 Conclusion

This chapter has concluded that the regulation of tourist activities in the Antarctic region below 60°S occurs in a number of different ways and through several other bodies, including the IAATO, the Antarctic Treaty itself, the Protocol on Environmental Protection (Madrid Protocol), which forms part of the ATS, as well as POLAR VIEW (which is a chapter of the Polar code). Furthermore, DNV aims to develop environmental sections supplemental to the polar code, which would ban the use of heavy fuel oil [5, 25]. The inter-governmental and inter-agency management of polar regions presents a unique challenge, and SAR exercises and related initiatives are essential in building relationships, trust and understanding.

Chapter 3: A Review of the Accidents Occurring in the Antarctic Region

3.1 Introduction

Following the steam engine's advent and the invention of various new materials and manufacturing processes, vessels were able to voyage further afield than ever before, ultimately revolutionising the shipbuilding and shipping world. The icebreaker was a further innovation, allowing travel into more hostile climates and ultimately culminating in the Antarctic research vessels (ARVs).

This chapter aims to review the number of accidents of vessels visiting the Antarctica areas based on literature review, statistic data published, and accidents reported. The objective is to identify the most accidental ship types visiting this area and ship casualties caused by the Antarctica area's harsh environment and provide recommendations for good practice when applying the polar code to ships operating in Antarctic waters.

These objectives can be achieved through:

- A review of both the type of vessel involved and the nature of the accident in Antarctic waters, including collapse, explosion, foundering or sinking.
- The evaluation of the historical frequency of such accident events; and
- An identification of any vessels which may have been lost as a result of the accident.

Australian scientific organisations are highly regarded worldwide, conducting more than 800 international scientific activities, many within Australia's borders, accounting for the top 1% of global scientific institutions researching 13 out of 22 research domains. Several organisations have been established as a result of Australia's scientific activity, including the Australian Antarctic Division, the Australian Astronomical Observatory, the Australian Institute of Marine Science, the Australian Nuclear Science and Technology Organisation, the Bureau of Metrology, Geoscience Australia, and the National Measurement Institute [29]. Australia strives to discover and explore areas of scientific knowledge currently unknown to researchers, a legacy that is continued with the work of the Australian Antarctic Division. Hobart's emergence as the gateway to Antarctica is due to Australia being well-positioned for missions to the Antarctic region, as the Australian continent is adjacent to the Antarctic and Southern Ocean regions, making resupply easy.

The Australian Antarctic Division provides opportunities to nearly all aspects of science and ingenuity [30]. Since its conception in 1947, the Australian National Antarctic Research Expeditions, a subdivision of the Australian Antarctic Division, has deployed a number of ARVs, either purpose-built or redesigned and modified vessels. Ensuring that a vessel meets the specifications of scientific research and being equipped for a variety of other activities requires that a number of procedures are put in place regarding both the crew and passengers to ensure everyone's safety. This can be seen in the requirements for vessels operating in harsh air temperature areas for long periods to be constructed from either steel or other approved ductile material due to the variety of stresses and strain factors that occur at lower temperatures. This class would have been put together with all the experiences from previous ships travelling to the polar regions generating a better understanding of how the ship's material works better in the known environment.

Over time, polar vessels have seen an exponential increase in equipment and system innovation; examples include the novel seawater cooling system, which plays the vital role of transferring heat away from the operating system. Innovation is limited in polar environments due to the presence of ice and low temperatures, thereby affecting the operation of the vessel's systems. This is particularly rampant in vessels navigating between warm and polar climates.

3.2 History of Antarctica Research Vessels

Significantly different in design from other vessels, icebreakers are used to transverse ice-covered waters at temperatures less than -2°C in the Antarctic and Arctic regions. Icebreakers are constructed with a thicker material or hull in order to withstand the impact of the floating ice rafts, so it can crush the ice directly in its path, as well as push the shards out of the way of the vessel to overcome any damage to the vessel's propellers and rudders. The earliest use of icebreakers is thought to be in the 11th century [31]. However, it was not until the advent of the steam engine in the 16th century that the vessels were able to plough into the ice with a fixed pitch and a screw-type propeller. Before steam, exploratory ships were not powerful or durable enough to crush through floating sea ice. This limitation was mitigated by an open water hull shape with sloping bows, creating enough vertical force to break the ice without restricting movement [32].

Early icebreaking vessels were constructed with wood reinforced by steel beams to strengthen the bows and stern. Heavy steel sheeting was also used to line the vessel to protect the relatively vulnerable timber hull. Modern-day polar vessels are constructed from steel though it requires specifically designed reinforced stiffening, which allows the ship to plough through the ice without being crippled under the engines' force [33]. As a result of global warming, the ice is also not as thick compared to 100 years ago, making it easier for icebreaking vessels to transverse polar regions [34].

Scientific readings and observations in meteorological and biological studies were previously undertaken through cracks in the Antarctic region's ice. The 1870 Pilot icebreaking vessel was the first to attract attention and was vital in communicating between Kronstadt and St. Petersburg (Figure 4). The Yermak has constructed under naval commander Makarov's supervision and moved to 81º21'N north of Spitsbergen in 1899. As shown in Figure 5, this was later exceeded when the Yermak moved to 83º06'N north nearly 40 years after construction [35].

Figure 4: The 1870 icebreaking vessel Pilot [36].

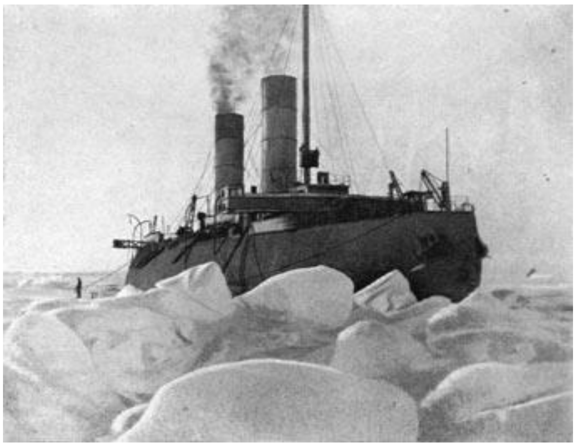

Figure 5: The Yermak icebreaking vessel [35].

The first expedition to Antarctica was led by Ernest Shackleton in 1901, who unfortunately fell ill with scurvy, and the voyage was aborted earlier than expected. Shackleton led a second expedition in 1907 on the vessel Nimrod. The crew set sail for New Zealand to gather supplies before commencing the isolated and arduous voyage to the Antarctic. However, the Nimrod was not an ideal vessel; it was chosen to fit within the voyage budget. During the voyage, the Nimrod came into contact with pack ice. To save coal, the Koonya was used to tow the Nimrod for a proportion of the voyage, illustrated in Figure 6 [35]. In the same year, Edgeworth David led an Antarctic party travelling 1260 miles with sleds and a motorised vehicle, as shown in Figure 7. They reached the southern magnetic pole on January 15, 1909 [35].

Figure 6: The Nimrod is moored in an ice footing [35].

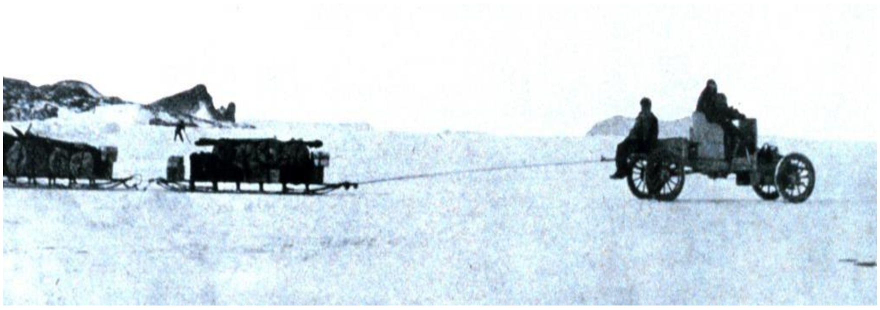

Figure 7: Edgeworth David with sleds and a motorised vehicle [37].

Sir Douglas Mawson (Figure 8) led the first Australian Antarctic Expedition between 1911 and 1914. Mawson had been a part of the Nimrod expedition of 1907 and intended to undertake scientific research on behalf of the British government. This provided the momentum for the collaboration between the British, Australian and New Zealand governments to undertake exploratory voyages in the Commonwealth's name. Collectively known as the British, Australian, New Zealand Research Expeditions (BANZARE), Mawson laid the foundation for all Australian Antarctic research expeditions in the years to come [38].

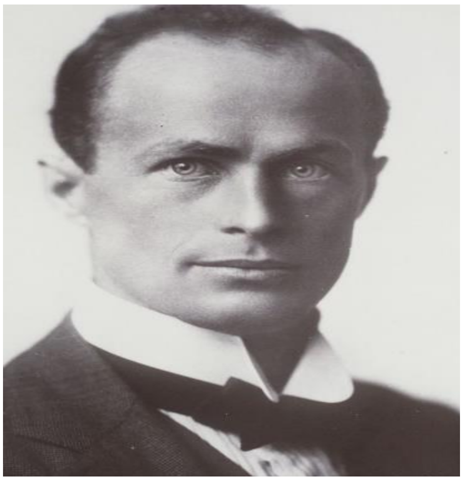

Figure 8: First Australian Antarctic expedition led by Sir Douglas Mawson (1882 - 1958) [30].

The first icebreaker was explicitly designed for scientific research expeditions in the polar code regions. The research vessel Polarstern (Figure 9) was first commissioned in 1982 [39] and conducted almost 300 expeditions between Arctic and Antarctic regions allocated for working in the polar area. Polarstern is still one of the most sophisticated polar research and supply vessels global scale, even though it has been operated in the polar area for over 35 years [37]. Besides, the other research vessel Healy accommodating a maximum of 50 researchers, was commissioned in the US in 1998, which set a precedent for specifically commissioning research vessels with icebreaking capacity, ultimately leading to the modern Australian icebreaker, the Nuyina [40].

Figure 9: The research vessel Polarstern [39].

The Australian research vessels with the ANARE banner survey the Antarctic coastline, resupply Antarctic continental and sub-Antarctic stations, oceanography, and marine science. This is administered through the department of agriculture as the main push for marine science in the Antarctic. The challenges associated with research and resupply have been mitigated by recent technological advancement and better ship design for the Antarctic conditions. Since

1947, about fifteen ARVs have been deployed to serve with the Canadian built HMALST 3501. The Aurora Australis, the flagship Australian Antarctic vessel, was launched in 1989 and is still in operation. The Nuyina [40] is part of the new generation of icebreakers demonstrated in Figure 10, which will further strengthen Australia's Antarctic capabilities [39]. Additionally, it will form part of the most significant investment in the Australian Antarctic Division to the tune of $1.9-billion and would allow Australians to conduct research within highly volatile weather areas, as well as enable passage through the sea ice problem, and ensuring that all persons aboard will survive the coldest Antarctic sea desserts for extended time periods. The Nuyina stands apart from other icebreakers as a result of its

> *... greater icebreaking and cargo capacity, increased endurance and operational flexibility, a high standard of environmental performance, and state-of-the-art research, rescue and resupply capabilities* [40].

Figure 10: New generation icebreaker RSV Nuyina [40].

3.3 Accidents in the Antarctic Region

Similar to an oil tanker, a bulk carrier, or even a cargo carrier, icebreakers are explicitly designed for the task of navigating the icy waters of polar regions. However, this does not make the icebreaker immune to the challenges, accidents, and hazards faced by the general shipping industry. The challenges can be split into three categories: weather, geographical, and technological. The aforementioned weather hazards exist in the form of strong storms, such as squalls, typhoons, hurricanes, and tsunamis. The Aurora Australis (Figure 11) ran aground in 2016 when she experienced extreme wind gusts of 130 km/hr. As a result, she broke free from her mooring and ran aground while remaining watertight, ensuring that no crew or passengers were harmed.

Figure 11: The Aurora Australis ran aground in 2016 [29].

Geographical hazards can acquire any structure that sits above the water or submerged in shallow enough water that the ship may interact with, including reefs or sandbars. This may also include weather hazards, with most incidents generally occurring due to a combination of hazards. Under heavy fog conditions in 2019, the Chinese icebreaker Xue Long collided with an iceberg travelling at 5.5 miles per hour, damaging the hull and inundating the deck with 250 metric tonnes of ice accumulated (Figure 12). The vessel and her passengers were otherwise fine and were eventually rescued.

Figure 12: The Xue Long collided with an iceberg [41].

Technological hazards can occur when the onboard equipment, such as the engine, fails. The US Coast Guard icebreaker experienced technical issues in 2011 when the engine failed and flooded due to an electrical system error (Figure 13). This refit cost the government $62 million [42].

Figure 13: The US coast guard icebreaker [42].

Only a small number of vessels sail in the Antarctic and Southern Ocean region due to the presence of unique hazards in the Antarctic. As discussed earlier, most ships are incapable of travelling into the region without specialised equipment and costly insurance. Without the assistance of icebreakers, traditional vessels sail through such water. In 2019, the European Maritime Safety Agency (EMSA) reported 23,073 casualties [43], including all victims of polar accidents, as well as ranging from low rated casualties to high rated casualties [43, 44]. As demonstrated in Figure 14, about 68.5% of shipping incidents occur globally scale due to human error, and 20% can be accounted for by system and equipment failure. It is difficult and costly to avoid technological incidents with regular maintenance and continually upgrading gear and equipment. The number of incidents is minimal in the context of the global scale of shipping, as shown in Figure 14. It shows the number of ship casualties from 2011 to 2018. There was a significant increase in the number of human action, about 2600 causes of most ship casualties [44]. The system equipment failure had 950 ship casualties, and other vessel had 500 ship casualties; however, the lowest of ship casualties had 300 between the year 2011 and 2018 [43].

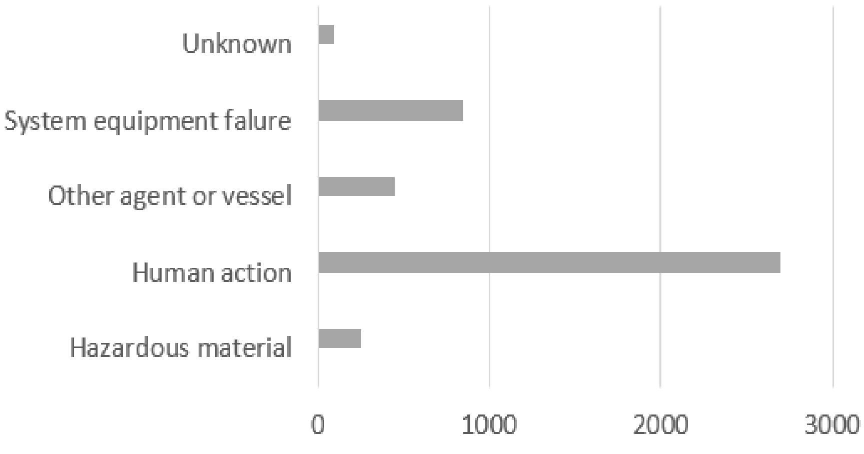

Figure 14: Global-scale ship casualties between 2011 and 2018 [44].

Figure 15 shows the number of accidents in Antarctica from 2011 to 2018. There is an increase in the number of fishing vessels lost, which is about 125. The majority of vessels lost at sea are fishing vessels, which generally require a small crew. However, the number of lost cargo vessel is about 39, and other types of vessels lost is about 37 in the Antarctic regions.

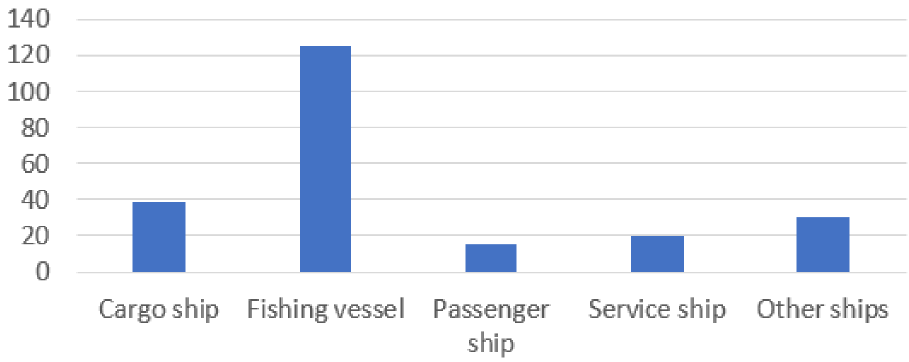

Figure 15: Different type of vessels lost between 2011 and 2018 [43, 44].

Figure 16 shows the most forms of error caused by weak social and safety awareness. Most crew members are not aware of their environment and surroundings, which has been the most significant liability. It is also vital that crews and staff should practise good ethics. As shown that human error can be prevented through proper training of crew and staff members; however, this does not prevent all incidents. Working crew and staff onboard polar vessels spend a long period of time at sea, a job that can be straining on both the individual and their families on shore.

Figure 16: Human error related cases between 2011 and 2018 [43, 44].

Icebreakers belong to the title of other categories. The Australian icebreaker Nuyina fits under the title of all categories as she carries her trawling equipment, stores cargo for the supply of Antarctic research bases, and carries many passengers and acts as a service ship. As a result, the Nuyina may pose a higher risk of a casualty due to a wide range of activities being carried out both internally and externally. While most icebreakers operate in a number of capacities, each ship's capabilities differ from one to another. In the case of an icebreaker, the best way to mitigate casualties in an emergency or accident is to learn from past events and apply the most current and appropriate knowledge and expertise to prevent further casualties in the future.

3.4 Incidents in Polar Waters from 2007 to 2015

Table 1 shows some examples of recent fishing vessel incidents and other non-SOLAS ship losses and incidents in polar waters [45].

Table 1: Examples of recent fishing vessels and other non-SOLAS ship losses and incidents in polar waters [45].

Vessel and flag	Incident, location, and date	Further information available
Argos Georgia, UK (fishing vessel)	Loss of power in the Ross Sea, Dec. 2007; spare parts airdropped to vessel.	ATCM XXXI IP52: Report of Main Engine Failure of FV Argos Georgia in the Ross Sea on 24 December 2007. Submitted by the United Kingdom.
In Sung 22, Republic of Korea (fishing vessel)	Fire onboard, Scotia Sea; SAR involved, June 2009.	CCAMLR XXVIII 30: Fire on Board The In Sung 22 in CCAMLR Statistical Subarea 48.3. Submitted by the United Kingdom.
Insung No 1, Republic of Korea (fishing vessel)	Sank with loss of 21 lives; fuel oil sank with ship north of Ross Sea; SAR involved, Dec. 2010.	CCAMLR XXX BG 34: Follow-up Information Regarding the Capsizal Incident of the Insung No.1. Submitted by Korea.
Berserk, Norway (yacht)	Lost, presumed sunk with three fatalities in the Ross Sea; would have carried some oil; SAR involved, Feb. 2011.	ATCM XXXIV IP18: The Berserk Incident, Ross Sea, February 2011. Submitted by New Zealand, Norway and the United States. ATCM XXXIV IP75: The Legal Aspects of the Berserk Expedition. Submitted by Norway.
Sparta, Russia (fishing vessel)	Holed in ice, Ross Sea, Antarctica; SAR involved, Dec. 2011.	ATCM XXXV WP 49: ATCM Response to CCAMLR Fishing Incidents. Submitted by New Zealand. ATCM XXXV IP 17: SAR Incidents in the 2011/12 Season: FV SPARTA and FV JEONG WOO. Submitted by New Zealand.
Jeong Woo 2, Republic of Korea (fishing vessel)	Fire, loss of three lives; presumed sunk with fuel oil, though possibly consumed by fire in the Ross Sea, Antarctica; SAR involved, January 2012.	ATCM XXXV WP 49: ATCM Response to CCAMLR Fishing Incidents. Submitted by New Zealand. ATCM XXXV IP 17: SAR Incidents in the 2011/12 Season: FV SPARTA and FV JEONG WOO. Submitted by New Zealand.
Brazilian oil barge, Brazil (oil barge)	Capsized and sank with 10,000 litres of diesel on board, South Shetland Islands, Feb. 2012; the barge was later recovered intact.	ATCM XXXV IP65: Comandante Ferraz Station: Oil Barge Incident. Submitted by Brazil.
Endless Sea, Brazil (motorised yacht)	Beset in ice and sank at King George Island, South Shetland Islands in April 2012 while carrying around 8,000 litres of fuel; SAR involved.	ATCM XXXV IP64: Brazilian Yacht Accident. Submitted by Brazil.
Kaixin, China (fishing vessel)	Caught fire and sank, in the Scotia Sea, in April 2013; fuel oil possibly all consumed by fire; SAR involved. The casualty investigation report in IMO's GISIS system refers to faulty wiring as the cause of the fire.	CCAMLR XXXII/BG/10: Summary report on the fire incident of the fishing vessel Kaixin. Submitted by the People's Republic of China.
Polonus, Poland (sailing yacht)	Sailing yacht was stranded in bad weather on King George Island, near a protected area (Antarctic Peninsula). All crew rescued and all fuel removed. December 2014.	ATCM XXXVIII_bp009 Polish Sailing Yacht Accident at King George Island (Antarctic Peninsula). Background paper submitted by Poland.

Antarctic Chieftain, Australia (fishing vessel)	Trapped in pack ice consisting of thick multi-year ice. Ice had contacted the propeller, resulting in damage to three of four blades that had no immediate threat to life's safety. A two-stage rescue was required – the nearest ice breaker was 430nm away. United States Coast Guard Cutter (USCGC) Polar Star arrived on the scene 3 days after the fishing vessel became trapped and commenced breaking the ice pack, following which the fishing vessel was towed/escorted clear of the ice. Stage 2 – fishing vessel escorted back to port in New Zealand, arriving 20 days after becoming trapped. February 2015.	ATCM38_ip051_e SAR Incident: Antarctic Chieftain (2015) at Christchurch in New Zealand area. Information Paper submitted by New Zealand.

3.5 Conclusion

The unique challenges presented by the polar regions require highly specialised equipment, experienced and knowledgeable crew members, and expensive and comprehensive insurance. Despite taking all precautions, the harsh environment presents an almost insurmountable hazard resulting in a vast number of accidents, with 68.5% global scale occurring due to human error or direct human action and 20% occurring as a result of system or equipment failure. Human error may be compounded onboard on an icebreaker such as the RSV Nuyinya with a wide range of activities. Such type of vessel participates in several internal and external missions, thus increasing the risk of an accident. In order to mitigate the risk, additional training is required to staff members and crew to reduce human error.

Chapter 4: The Harsh Environmental Conditions of the Antarctic Region

4.1 Introduction

Best known for its plethora of both living and mineral resources, the Antarctic region's harvesting and exploitation operations face considerable challenges and safety risks. In order to mitigate these environmental challenges, additional design and operational arrangements are required to reduce disruptions and potential hazards. When comparing Antarctic systems to the same system operating in a more temperate or tropical region, it can be seen that conditions such as extreme weather and remoteness [46] negatively affects the mental attitude and work efficiency of the personnel, thereby labelling human error as a contributing factor to accidents and emergencies [47]. Risk factors unique to the Antarctic environment make resilience assessments a higher priority than risk assessments [47].

This chapter aims to review the type and frequency of vessels visiting the Antarctica areas, their routes, operations, and the winterisation of different Antarctica vessels. The objective is to identify the most common ship types which are visiting this area with their missions and assisting them in the harsh environment of the Antarctica area.

These objectives can be achieved through:

- A review into the most common routes taken by vessels throughout the region, as well as differentiating between destinations across three summer seasons, with the most common destinations including the Antarctic Peninsula, the Ross Sea, South George, the Weddell Sea, and the Southern Ocean;
- The survey of vessel types travelling throughout the region between 2016 and 2019;
- The analysis of statistical data collected during the 2016 summer season regarding vessel accidents and casualties in the Southern Ocean;
- The identification of accident trends within the Southern Ocean, specifically within the predefined areas 103 and 104 respectively;
- The identification of key stakeholders, and the subsequent mapping of relationships and dependencies in the Antarctic region; and

4.2 Background of Winterisation in the Polar Waters

The IMO has adopted the international code for ships operating in polar waters (polar code) [6], as well as all related amendments, thus making its enforcement mandatory under the

SOLAS [48, 49], as well as the MARPOL. After entering into force in 2017, the polar code marked a historic milestone in protecting vessels operating in polar waters and all passengers and crew aboard. Adopted at the November 2014 session of IMO's Maritime Safety Committee (MSC) [50], the polar code and SOLAS provisions were further amended as part of the 68th session of the MEPC in May of 2015 [51].

In order to protect the Antarctic and Arctic regions and keep safe, several risk-based approaches for the polar code regions [52] were developed by IMO and available to-date, including the 2002 and 2010 voluntary guidelines. These guidelines also include existing treaties regarding safety, and environmental protection, such as the International Convention for the Safety of Life at Sea or (SOLAS) and the International Convention for the Prevention of Pollution From Ships (MARPOL), 1973 as modified by the Protocol of 1978.

The shipping regulation framework developed by IMO maps the transition from authoritarian to development approaches. The polar code was initially developed to cover all manner of considerations regarding vessels' operation in polar waters, including construction, design, environmental protection, equipment, operation, training, and SAR; however, it wasn't included vessels entitled to sovereign immunity, fishing crafts, and weighs less than 500GT. While several environmental protections are currently in place in the Antarctic region, many are not yet in practice for the northern Arctic region. For example, a 2010 protective measure adopted by the MEPC restricts the use and pollution of heavy grade oils in the Antarctic region, though it does not apply to pollution in the Arctic [51].

The IMO workshop on the environmental aspects of the polar code was held in Cambridge, United Kingdom, in September 2011 as part of the ongoing international workshop on shipping safety in polar regions. All reports and presentations related to the workshop can be found on the IMO's website. The MSC [53] released a 2012 report which detailed all work and advancement on the polar code. The MSC decided, as of 2012, to "keep any decision on environmental requirements to be included in the code in abeyance, pending further consideration at DE 57 [54]". The MSC finally approved the polar code in November 2014; however, it only came into effect in 2017 and 2018 for new and existing ships, respectively [55]. The first ship to be certified as part of the code was the Russian shuttle tanker, the Shturman Albanov, in December of 2016. Many industry bodies and environmental groups regarded the code as being "too weak" and "diluted" due to the pollution requirements being particularly lax, allowing ships to dispose of waste overboard so long as the vessel remains 12 miles from the Arctic ice. The structural requirements were also thought to be incredibly lenient, as vessels making passage through the Arctic were not required to be ice-classed. Polar certification does not require a separate physical survey, and the polar code allows this to be simply sent ahead. Furthermore, the code does not address several vessels fitting certain specifications, such as those less than 500GT, and not mentioning emissions and air pollution. While the polar code does list recommendations regarding ballast water management and anti-fouling paint, the choice of whether or not to comply is left to the vessel operators rather than an independent party.

To resolve the lack of regulation in the Arctic, the IMO developed and implemented guidelines in 2002, which only apply to vessels in the region [55]. These guidelines were expanded in 2004 after a request from the ATCP [56]. The significance of mandating certain guidelines was seen while the IMO attempted to expand their reach to Antarctic waters [53], in that sinking of the M/V Explorer in the Antarctic waters [57] and the sinking of the M/S Explorer in the Arctic waters [58] may have been prevented. As a result of the accident, the MSC instructed the development of mandatory regulations for those vessels operating in both polar regions [55]. This concluded with the establishment of the "International Code of Safety for Ships Operating in Polar Waters" in February 2010 by the DE sub-committee, as well as an inter-sessional correspondence group [54, 59].

To better ensure the safety of polar vessels, the polar code addresses issues related to construction, design, equipment, maintenance, and operations as well as environmental protection in the form of guidelines regarding the controlled use of oil, invasive species, sewage, garbage and chemicals [60]. As dictated by chapter 6 of the polar code manual, machinery installations require the specific application of the guidelines. This can be seen in all machinery installations that must prove to be functional under a wide range of anticipated environmental conditions, including ice and snow accretion or accumulation, ice and snow ingestion from seawater, the increased viscosity of liquids as a result of various freezing stages, and the temperature of seawater intake. The functionality of all machinery in hostile environments includes the cold and dense inlet air, as well as any loss of performance regarding an installed battery or other energy storage device. The polar code further states that the materials used are required to be suitable for operation at the ship's polar service temperature (PST). All these requirements and guidelines, however, unable to stave off an accident as illustrated by the CLIA report to IMO, which concluded that a range of factors might be involved in an accident or emergency, including poor weather conditions, poor charting, impediment of vision in the case of darkness or fog, equipment failure, and human error [60].

Ice-strengthened vessels require that all machinery installations must provide functionality under hostile environmental conditions and consider loads imposed directly by ice interaction. The polar code also dictates that machinery installations and associated equipment must be protected against the aforementioned effects. For more details, see chapter 6 of MEPC 68/21/Add.1Annex 10. Further chapters relating to the risk posed to the environment by vessel operations and the risk posed to vessel operations by extreme environmental hazards would be developed by DNV, including the ban of heavy fuel oil, which has been introduced in the Antarctic region [60].

4.3 The International Code for the Safety of Ships Operating in Polar Waters

The operation of vessels in and around the Antarctic and Arctic regions have always been a matter of concern for the IMO, as a result of harsh and inhospitable weather conditions, a distinct lack of infrastructure, remoteness and isolation from land, darkness and the distinct lack of accurate charts relative to other areas of the globe, as well as the challenges presented by communication systems and other navigational aids [61]. The aforementioned challenges increase SAR risks [62, 63] and make clean-up operations demanding and expensive. The hostile weather conditions and reduced air temperatures have been seen to decrease the effectiveness of a number of vessel components, including deck machinery and equipment required in emergency scenarios. The presence of ice presents a unique obstacle in that it may impose additional loads on the vessel as a whole, especially on the hull and propulsion system.

Despite the risks, the demand for resources and tourism has presented a unique market for the merchant, cruise and offshore vessels to operate in polar regions. Maritime transportation has revolutionised inter-continental trade and overseas tourism industries [64]. Regulated by SOLAS and the MARPOL, vessels operating in international waterways and the high seas [65] still face a significant threat of accidents and injuries. While several regional and international bodies control shipping operations, there are many accidents reported annually. This is especially true for vessels operating in the polar and sub-polar regions, as they are more prone to accidental loss or emergency due to extreme weather conditions. To mitigate such accidents, a number of regulatory authorities have introduced guidelines and amendments aimed at shipping practice in certain geographical areas [26, 65]. For instance, the polar code aims to regulate vessels moving through the ice-covered regions of the Arctic and Antarctica [27, 65]. The Arctic council's report [17] identifies shipping related accidents and their causes, in addition to a discussion on the prospects of shipping in this region and its brief history. Winterisation guidelines have identified that vessel systems have been negatively affected through general operation in harsh environments. Therefore, it has been suggested operation by different sources to identify interface systems and sub-systems that may be influenced by the winterisation process [6, 66], such as the following:

- RMRS' (Russian Classification Society) Requirements for Ship Equipment to Ensure Long-term Operation at Low Temperature;
- DNV's (Norwegian Classification Society) Ice Class Rules– Sections 5,6 and 7, Winterization and Design Ambient Temperature (DAT);
- ISO 19906: Petroleum and natural gas industries—Arctic offshore structures (International Arctic Offshore Structures Standard); and
- IMO's Guidelines for Ships Operating in Polar waters.

The above-published works focus primarily on establishing the requirements for winterisation associated with shipping operations in the Arctic and Antarctic regions, allowing for the review of a vessel's compliance with the guidelines to avoid or mitigate the problems listed. The American Bureau of Shipping (ABS) and the Norwegian Classification Society (DNV) have provided guidance for vessels operating in low-temperature environments [6, 67]. Several shipping industries operate within the Northern Arctic region, including bulk carriers, general cargo operations, offshore oil and gas extraction, oil tankers, and LNG carriers that can be operated in various environmental conditions. Kum and Sahin [68] have analysed the causes of Arctic marine transportation accidents, which includes poor weather conditions, lack of communication and navigational aid, sub-zero temperatures coupled with some root causes for the collision or grounding of vessels, machinery failure as well as fires or explosion.

4.4 Locations, Destinations, and Routes Taken when Visiting Antarctic Regions

A number of vessels outside of transportation industries operate within the Antarctic and Southern Ocean region, including cruise liners, research vessels, and numerous species-specific fishing vessels. For the purpose of this thesis, missions originating from Ushuaia before making the journey through the Falkland Islands and the Georgia Islands and arriving at the Antarctic Peninsula and heading back to Ushuaia will be analysed as part of the case study [69-78]. In Figure 17, the average air temperatures during November, January and March in the annual summer season is represented as a function of the environmental conditions across six Antarctic destinations, which is distributed both seasonally and locally in the Southern Ocean based on weather reports collected between 1985 and 2015 [69-78]. From Figure 17, it is clear that the average air temperature in January is higher than both November and March in Falklands-Malvinas. Furthermore, while most temperatures were recorded as positive, however, in the Antarctica Peninsula, both November and March recorded negative average air temperatures, -2.5°C and 1.5°C, respectively.

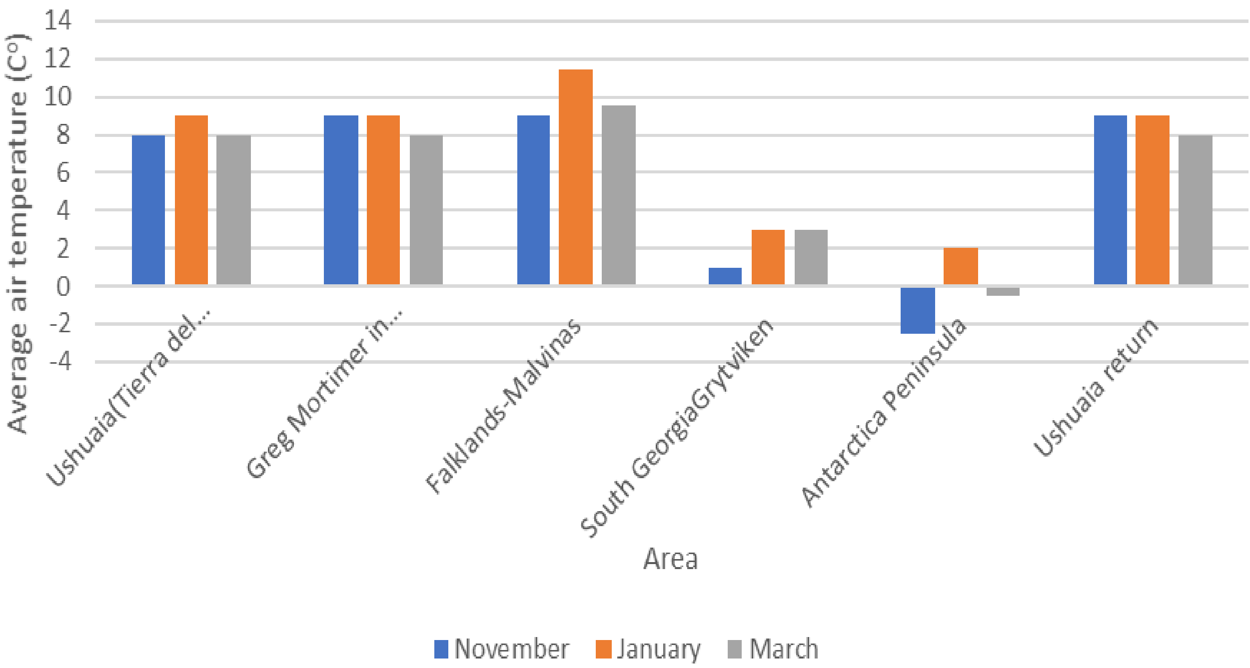

Figure 17: Seasonal and localised air temperature distributions in Southern Ocean areas [69-78].

Figure 18 shows the average wind speed across the six destinations during the annual summer season, considering seasonal and locational distributions based on weather reports collected between 1985 and 2015 [69-78]. It can be seen that the Falklands region experienced greater wind speeds across all three months—an approximate increase in wind speeds of 32% in Falklands-Malvinas and also in November, a 28% increase e in wind speeds in January, and a 27% increase in March in wind speeds at the same destination—while South Georgia destination experienced slower wind speeds in November based on weather reports collected between 1985 and 2015 [69-78].

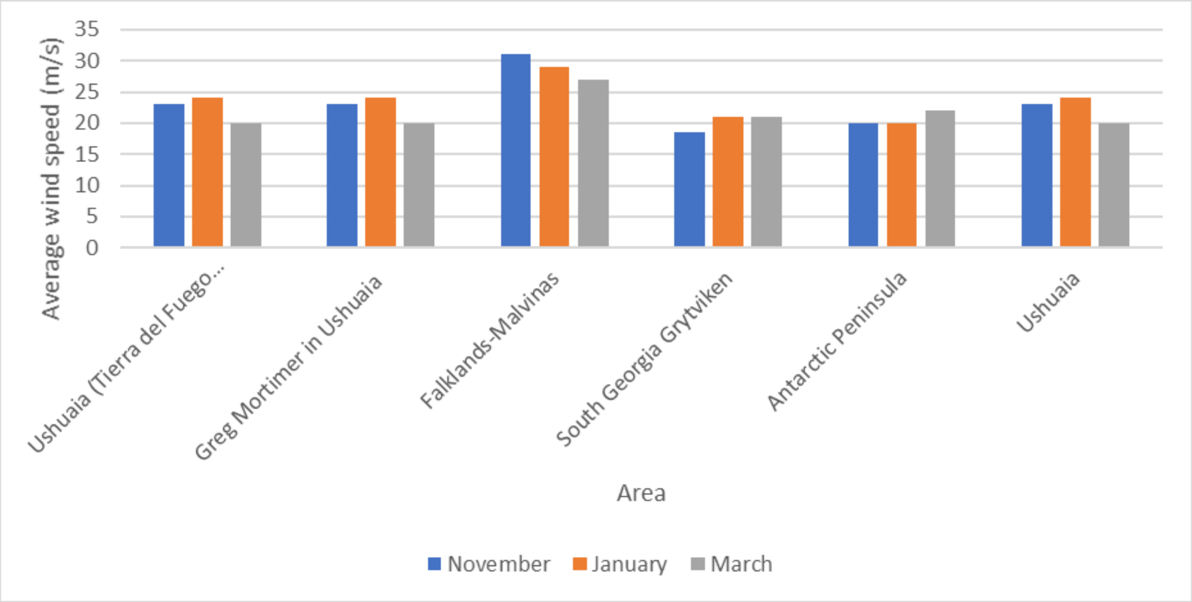

Figure 18: Average wind speed in the Antarctic and Southern Ocean region during the summer season [69-78].

Figure 19 demonstrates the route taken by the majority of cruise ships, with missions originating from Ushuaia before making the journey through the Falkland Islands and the Georgia Islands, arriving at the Antarctic Peninsula and then heading back to Ushuaia which will be analysed as part of the case study. It also demonstrates the most frequent route undertaken by cruise vessel when visiting the Antarctic region, travelling to four destinations denoted by numbers one through four. Table 2-4 in the next section would demonstrate environmental conditions data collected during such trips as described above.

Figure 19: A cruise liner route originating from Ushuaia in Antarctica regions.

4.5 Environmental Conditions Data Relating to the Southern Ocean and Antarctic Region

This thesis aimed to identify the harsh environmental conditions that may affect vessels operation in the Antarctic and Southern Ocean region, including cruise liners, research vessels, and numerous species-specific fishing vessels. In the following section, Table 2-4 has provided environmental conditions encountered by vessels based on weather reports collected between 1985 and 2015 [69-78]. Thus, the specific conditions relating to unique missions may be identified.

Table 2: Information of an early-season mission (November) for itinerary routes with different destinations from Ushuaia to Falklands-Malvinas to South Georgia to the Antarctic Peninsula and then return in Ushuaia, including the environmental season conditions.

Activities	Days spent	Destination	Average air temperature	Average sea temperature	Average humidity	Average wind	Average snow conditions	Average pressure
1-Passenger boarding 2-Departing quay 3-Manoeuvring 4-Transit and navigation in coastal waters (without tug) Transit in the open sea	1	Ushuaia (Tierra del Fuego National Park) island	3 to 13ºC [72]	5 to 13 ºC [69]	68% [69]	23 km/h [69]	No snow [69]	997 mbar [69]
2-Arriving in port Mooring 1-Passenger boarding (if applicable) 2-Departing quay 3-Manoeuvring Transit in the open sea	1	Greg Mortimer in Ushuaia	5°C to 13 °C [69]	5 to 13 ºC [69]	68% [69]	23 km/h [69]	No snow [69]	997 mbar [69]
2-Arriving in port 4-Mooring 2-Departing quay 3-Manoeuvring Transit in the open sea	1	Falklands-Malvinas	5 to13°C [79]	4 to 13°C [70]	69% [70]	31km/h [70]	No snow (Max of 2.6 cm in 2009) [70]	999 mbar [70]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in the open sea	3	South Georgia Grytviken	0 to 2°C [75]	0.5 to 2.2°C [75]	70% [74]	18.5 km/h [70]	0.3 cm [75]	998 mbar [71]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in the open sea	4	Antarctic Peninsula	-6 to 1°C [80]	0.7 to 3.2 °C [77]	78% [80]	20 km/h [78]		1000 mbar [78]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in the open sea	1	Ushuaia	5°C to 13 °C [69]	5 to 13 ºC [69]	68% [69]	23 km/h [69]	No snow [81]	997 mbar [69]
2-Arriving in port 6- Mooring and unloading								

Table 3: Information of a mid-season mission (January) for an itinerary route with different destinations from Ushuaia to Falklands-Malvinas to South Georgia to the Antarctic Peninsula and then return in Ushuaia, including the environmental season conditions.

Activities	Days spent	Destination	Average Air temperature	Average Sea temperature	Average Humidity	Average Wind	Average Snow conditions	Average Pressure
1-Passenger boarding 2-Departing quay 3-Manoeuvring	1	Ushuaia (Tierra del Fuego National Park) island	5°C to 13°C [69]	8°C to 17ºC [69]	70 % [69]	24 km/h [69]	No snow [81]	997 mbar [69]
2-Arriving in port Mooring 1-Passenger boarding (if applicable) 2-Departing quay 3-Manoeuvring Transit in open sea	1	Greg Mortimer in Ushuaia	5°C to 13°C [69]	8°C to 17ºC [82]	70 % [82]	24 km/h [69]	No snow [81]	997 mbar [69]
2-Arriving in port 4-Mooring 2-Departing quay 3-Manoeuvring Transit in open sea	1	Falklands-Malvinas	8°C to 15°C [79]	7°C to 17°C [70]	71% [70]	29km/h [70]	No snow [70]	1001 mbar [70]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in open sea	3	South Georgia Grytviken	2°C to 4°C [75]	0.7°C to 5.5°C [75]	77% [74]	21km/h [71]	No snow [75]	1004 mbar [71]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in open sea	4	Antarctic Peninsula	0°C to 4°C [80]	2°C to 4°C [77]	74% [80]	20 km/h [78]	0.3mm	1000 mbar [78]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in open sea 2-Arriving in port 6-Mooring and unloading	1	Ushuaia	5°C to 13°C [69]	8°C to 17ºC [69]	70 % [69]	24 km/h [69]	No snow [81]	997 mbar [69]

Table 4: Information of the late-season mission (March) for an itinerary route with different destinations from Ushuaia to Falklands-Malvinas to South Georgia to the Antarctic Peninsula and then return in Ushuaia, including the environmental season conditions.

Activities	Days spent	Destination	Average Air temperature	Average Sea temperature	Average Humidity	Average Wind	Average Snow conditions	Average Pressure
1-Passenger boarding 2-Departing quay 3-Manoeuvring Transit in open sea	1	Ushuaia (Tierra del Fuego National Park) island	3 to 13ºC [72]	7 to 14ºC [69]	74% [69]	20 km/h [69]	No snow [81]	999 mbar [69]
2-Arriving in port Mooring 1-Passenger boarding (if applicable) 2-Departing quay 3-Manoeuvring Transit in open sea	1	Greg Mortimer in Ushuaia	3 to 13ºC [72]	7 to 14ºC [69]	74% [69]	20 km/h [69]	No snow [81]	999 mbar [69]
2-Arriving in port 4-Mooring 2-Departing quay 3-Manoeuvring Transit in the open sea	1	Falklands-Malvinas	6 to 13ºC [79]	5 to 15ºC [70]	75% [70]	27 km/h [70]	No snow [70]	1002 mbar [70]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring Transit in open sea	3	South Georgia Grytviken	2 to 4°C [75]	0.6 to 4.4°C [75]	75% [74]	21 km/h [71]	No snow [75]	1004 mbar [71]
2-Arriving in port	4	Antarctic Peninsula			78% [80]	22 km/h		1000 mbar

Activities	Days spent	Destination	Average Air temperature	Average Sea temperature	Average Humidity	Average Wind	Average Snow conditions	Average Pressure
6-Mooring 2-Departing quay 3-Manoeuvring			-3 to 2°C [80]	2.5 to 4.3 °C [77]		[78]		[78]
2-Arriving in port 6-Mooring 2-Departing quay 3-Manoeuvring	1	Ushuaia	3 to 13ºC [72]	7 to 14ºC [69]	74% [69]	20 km/h [69]	No snow [81]	999 mbar [69]

Figure 20 illustrates a bar graph that depicts the probability distribution, P(H) of mean wave height H (m) during summertime from December to February in the Southern Ocean. Table 5 represents the wave height of areas 103 and 104 from December to February. The data source of significant wave height, H_s (m) and Zero cross wave period, T_z (s), is derived from the sea state source [83, 84]. Hence, a scatter diagram has been plotted, as shown in Table 6 using this data. The H_s and T_z values are class midpoints.

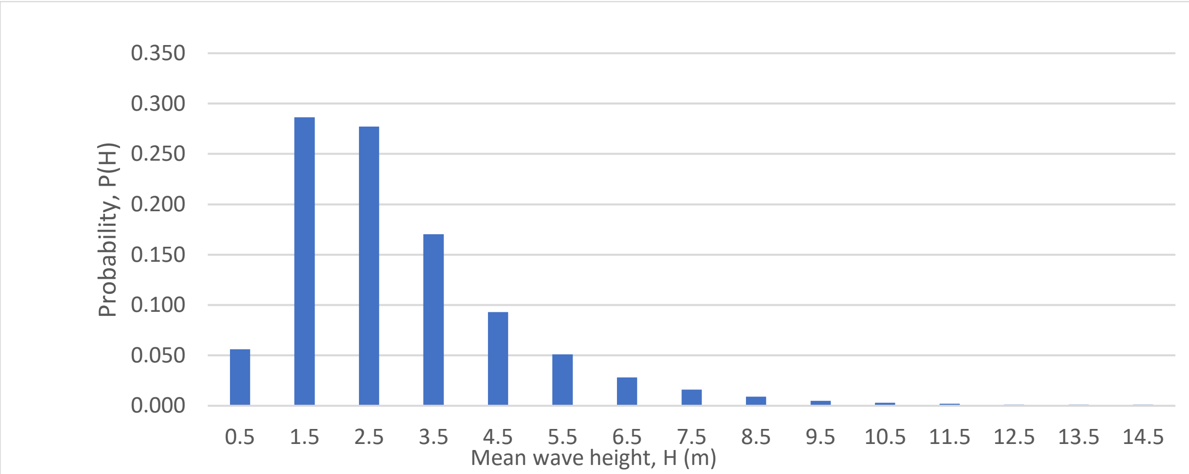

Figure 20: Distribution of mean wave height of areas 103 and 104.

Table 5: Wave height of areas 103 and 104 from December to February.

Wave height, H (m)	Number of wave height recorded (n)	Wave height average (m)	$H_{mean} = \bar{H}$ (m)
0-1	56	0.5	28.0
1-2	286	1.5	429.0
2-3	277	2.5	692.5
3-4	170	3.5	595.0
4-5	93	4.5	418.5
5-6	51	5.5	280.5
6-7	28	6.5	182.0
7-8	16	7.5	120.0
8-9	9	8.5	76.5
9-10	5	9.5	47.5
10-11	3	10.5	31.5
11-12	2	11.5	23.0
12-13	1	12.5	12.5
13-14	1	13.5	13.5
14-15	1	14.5	14.5

Where the total number of wave height recorded (n) = 999

- Mean wave height $H_{\text{mean}} = \bar{H}$

$$= (0.5 \times 56 + 1.5 \times 286 + 2.5 \times 277 + 3.5 \times 170 + 4.5 \times 93 + 5.5 \times 51 + 6.5 \times 28 + 7.5 \times 16$$
$$+8.5 \times 9 + 9.5 \times 5 + 10.5 \times 3 + 11.5 \times 2 + 12.5 \times 1 + 13.5 \times 1 + 14.5 \times 1)/999$$
$$= 2.95 \text{ m}$$

- Significant wave height, $H_s = H_{1/3}$

$$= \frac{16 \times 7.5 + 9 \times 8.5 + 5 \times 9.5 + 3 \times 10.5 + 2 \times 11.5 + 1 \times 12.5 + 1 + 1 \times 13.5 + 1 \times 14.5}{38}$$
$$= 3.24 \text{ m}$$

Table 6: Scatter diagram for observations of significant wave height and zero-up-crossing period for worldwide trade.

Significant Wave Height (m)	Interval of the zero-up-crossing period (s)														
	0 - 3.5	3.5 - 4.5	4.5 - 5.5	5.5 - 6.5	6.5 - 7.5	7.5 - 8.5	8.5 - 9.5	9.5 - 10.5	10.5 - 11.5	11.5 - 12.5	12. 5 - 13.5	13.5 - 14.5	14.5 - 15.5	15.5 - 16.5	16.5 - 17.5
0 - 1	311	2734	6402	7132	5071	2711	1202	470	169	57	19	6	2	1	0
1 - 2	20	764	4453	8841	9045	6020	3000	1225	435	140	42	12	3	1	0
2 - 3	0	57	902	3474	5549	4973	3004	1377	518	169	50	14	4	1	0
3 - 4	0	4	150	1007	2401	2881	2156	1154	485	171	53	15	4	1	0
4 - 5	0	0	25	258	859	1338	1230	776	372	146	49	15	4	1	0
5 - 6	0	0	4	63	277	540	597	440	240	105	39	13	4	1	0
6 - 7	0	0	1	15	84	198	258	219	136	66	27	10	3	1	0
7 - 8	0	0	0	4	25	69	103	99	69	37	17	6	2	1	0
8 - 9	0	0	0	1	7	23	39	42	32	19	9	4	1	1	0
9 - 10	0	0	0	0	2	7	14	16	14	9	5	2	1	0	0
10 - 11	0	0	0	0	1	2	5	6	6	4	2	1	1	0	0
11 - 12	0	0	0	0	0	1	2	2	2	2	1	1	0	0	0
12 - 13	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
13 - 14	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

Figure 21 demonstrates the number of vessels traversing the Antarctic region between 2016 and 2019 during the summertime from December to February in the Southern Ocean regions. Overall, an increase can be seen in the number of trips made by a large number of vessels, aside from the research expeditions in 2018, which undertook the lowest number of trips in 2019. It should be noted that this is not yet a full year's data. Also, Figure 22 demonstrates the number of trips by vessels in order to reach specific destinations within the Antarctic region in the summer season in three months between November, January, and March, also named the Antarctic Peninsula, the Ross Sea, South George, the Weddell Sea, and the Southern Ocean. It can be seen that the Antarctic Peninsula was the most attractive destination to tourists, with more than 300 trips undertaken. The second most popular destination was the Ross Sea, where most trips (100) were undertaken by research vessels in the summer season. South Georgia and the Weddle Sea were much less attractive in comparison. Based on the information provided in Figure 22, it can be concluded that the key destination for Antarctic travel is the Antarctica Peninsula summer season, with a yearly total of 322 trips made by a variety of vessels. On the other hand, the Ross Sea region was the most common destination for research and resupply vessels (with more than 100 trips) and fishing vessels (47 trips) [85-87].

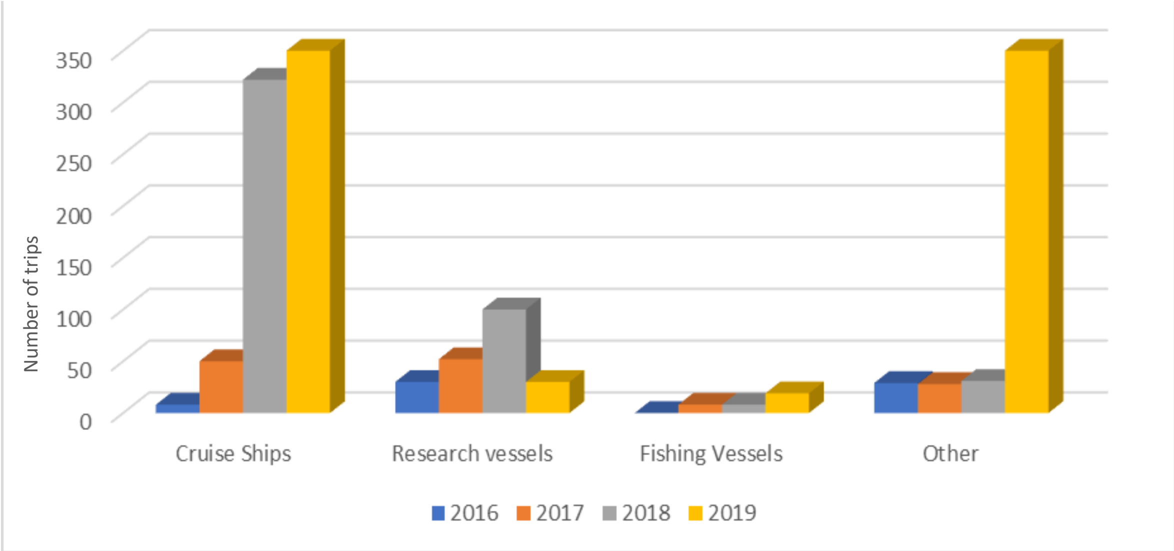

Figure 21: Number of vessel trips to the Antarctic region between 2016 and 2019 [85, 86, 88, 89].

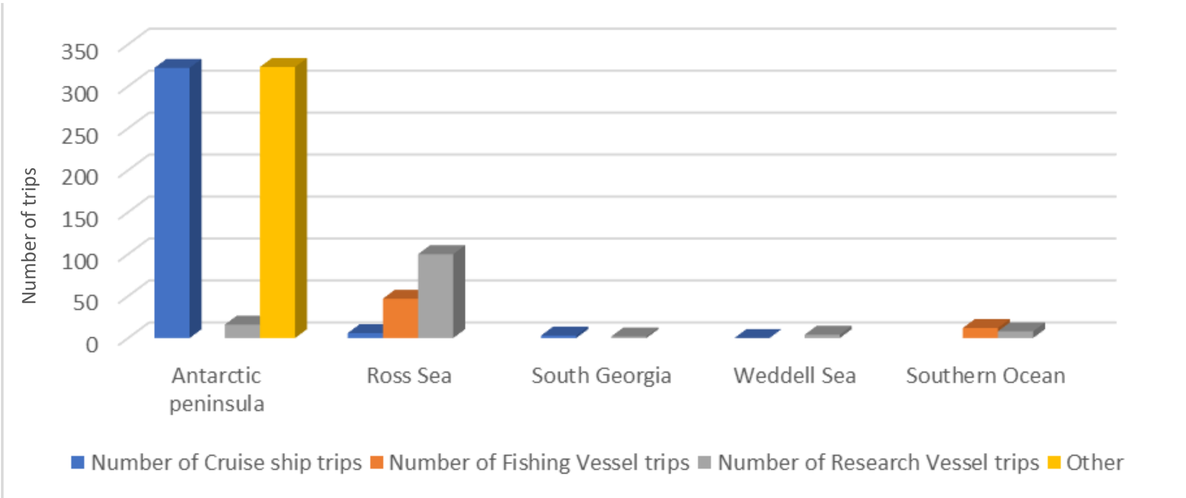

Figure 22: Number of trips across several Antarctic destinations [85-87].

The bar chart in Figure 23 demonstrates the humidity (%) in the summer season between November, January, and March for the six destinations in the ocean areas. Based on the case study provided, information was collected for six destinations in the ocean areas [69-78]. It can be seen that Ushuaia, Greg Mortimer and Falklands had an increase in humidity over the summer. On the other hand, South Georgia had a significant increase in January (approx. 77%) compared to November and March. Furthermore, the Antarctica Peninsula saw a significant increase in November and March and a slight drop in January (approx. 74%).

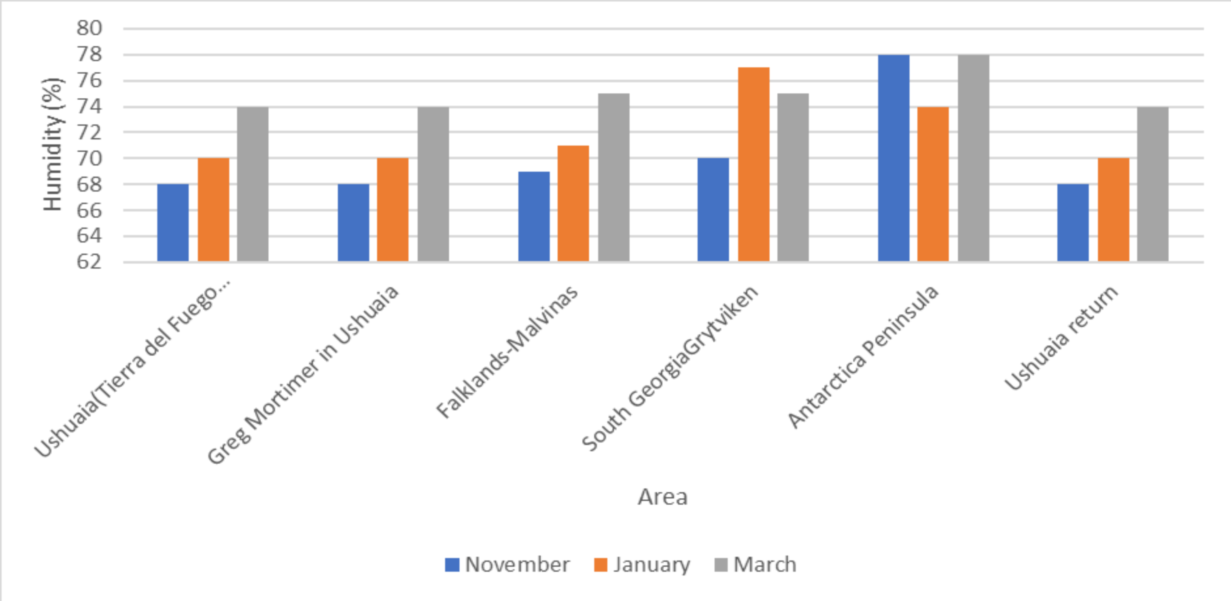

Figure 23: Seasonal and locational probability distributions of humidity for summer seasons [69-78].

4.6 Salinity and Temperature of Seawater in a Variety of Oceanic Areas

In Table 7, the salinity and temperature of seawater in a variety of oceanic areas have been included. From the table, it can be seen that a number of areas in the Antarctica region had a salinity range between 33.8 ppt and 34.7 ppt, such that the Antarctic bottom water had a salinity of 34.7 ppt at a temperature of -0.4°C, the Antarctic circumpolar water had a salinity range of 34.6-34.7 ppt at a temperature range of 0-2.0°C and also had a salinity range of 33.8-34.7 ppt at a temperature range of 3-7°C.

Table 7: Salinity and temperature of seawater in various oceanic areas [90, 91].

Water	Temperature (ºC)	Salinity (ppt)
North Atlantic Central Water	8.0 – 19.0	35.1-36.5
Antarctic Circumpolar Water	0.0 – 2.0	34.6-34.7
Antarctic Intermediate Water	3.0 – 7.0	33.8-34.7
North Pacific Intermediate Water	4.0 – 10.0	34.0-34.5
North Atlantic Deep Water	2.0 – 4.0	34.8-35.1
Antarctic Bottom Water	-0.4	34.7

The surface salinity (ppt) of the global scale ocean shown in Figure 24 demonstrates a regular pattern that depends on latitude emerges, with maximum values found in each ocean basin's centre and minimal values at the equator and the polar code regions [92].

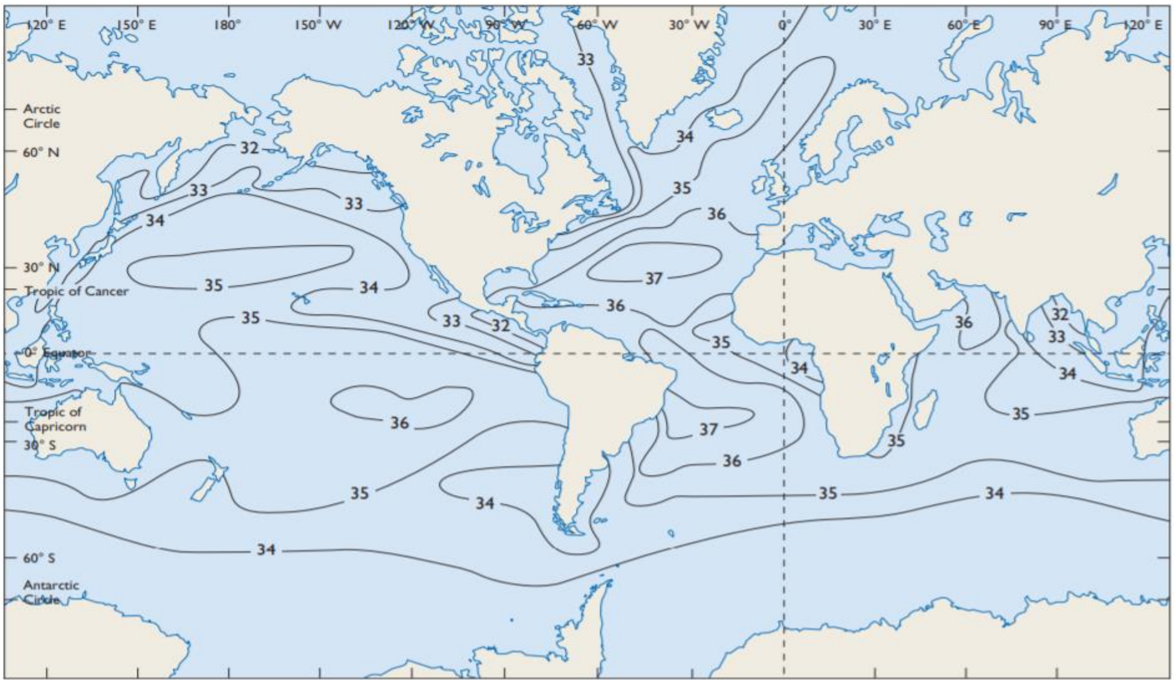

Figure 24: Surface salinity of the global scale ocean as represented in parts per thousand (ppt).

Wind speed is an important attribute of the environment. While wind cannot cool an object below the ambient temperature of the surrounding environment, it will reduce the rate of heat loss to the surrounding environment, thereby providing a cooling effect. The concept of wind chill is a measure of the combined effect of the lowered temperature and wind [93]. Also, humidity has to be humidity/water for the icing to occur. Seaspray is the major source of humidity/water to vessel systems. Spray icing has been an important research subject for many years [94], and researchers have studied the salinity and growth rate of spray ice. A model for generating the spray resulting from ship-wave collisions was used to determine the maximum height of the spray source above the ship deck [95]. The Southern Ocean regions are divided into two areas such as 103 and 104 as shown in Figure 25 which is critical for the operation of a cruise ship in the Antarctic area [92, 96]. This figure also shows a number of environmental conditions that may be encountered by a cruise vessel, namely the Greg Mortimer-Aurora Expedition, while travelling along identified Antarctic routes [87]. Based on the literature review, common routes and destinations need to be across six Antarctic destinations during the annual summer season in the Southern Ocean regions and must focus on these areas that can be operated easily in these locations also in this research focus on these areas only.

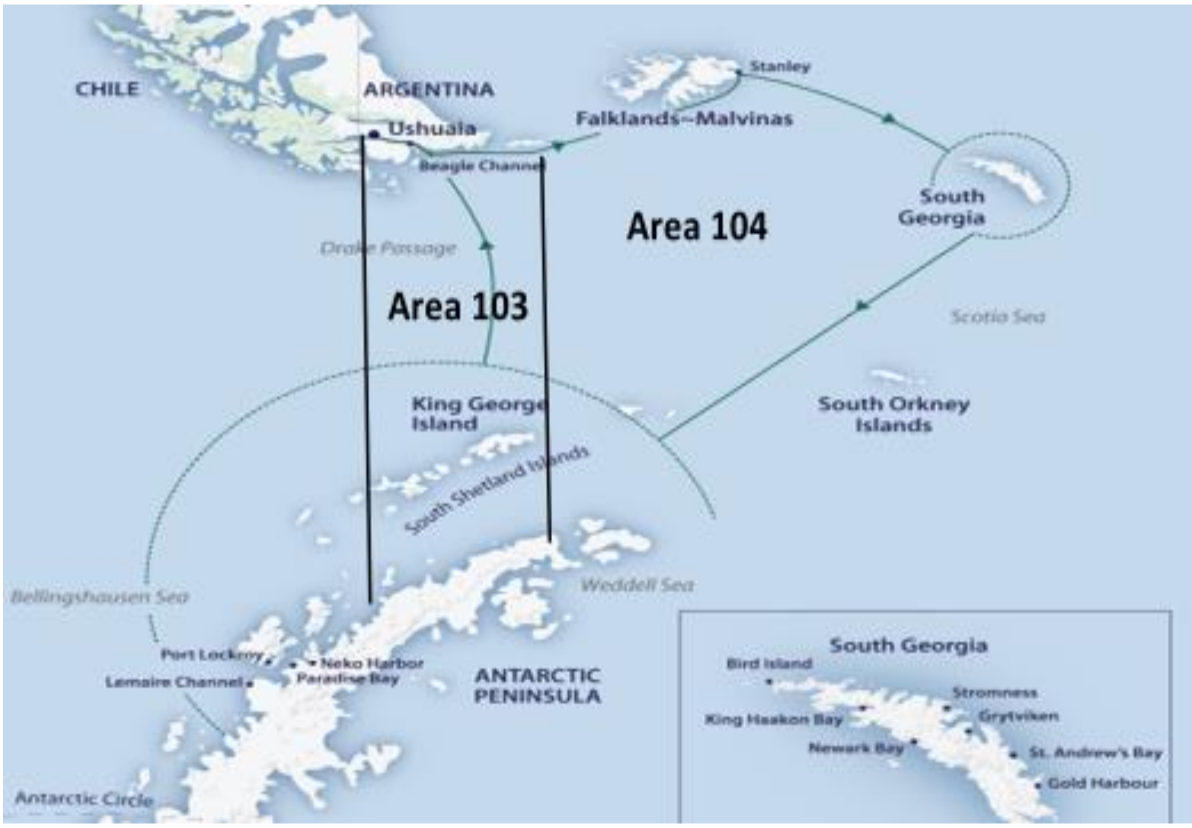

Figure 25: Mission and routes for cruise vessels.

4.7 Stakeholders and a Definition of Relationships and Dependencies

According to Figure 26 and Table 8, IACS provides stakeholders with a number of services both in classification and statutory and assistance to the maritime industry and regulatory bodies in regard to marine safety and pollution prevention. This is based on the accumulation of current marine knowledge and modern technology, which provides information for the stakeholders who intended to operate their vessels in the Antarctic/Arctic regions.

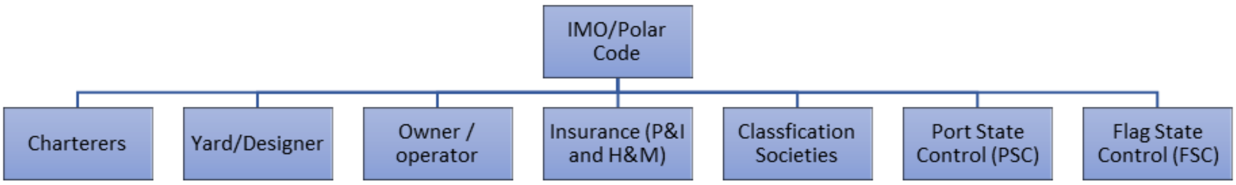

Figure 26: Major stakeholders.

Table 8: Stakeholders and a Definition of Relationships and Dependencies.

Stakeholders	Reason	References
Class	The IACS provides a number of services, including classification and statutory, and assistance to both the maritime industry and regulatory bodies regarding marine safety and pollution prevention, based on the accumulation of current marine knowledge and modern technology.	[96]
Clubs (P&I and H&M)	Marine insurance aims to reduce financial loss as a result of possible loss of cargo.	[97]
Chief Engineer	Holds total responsibility for all machinery maintenance onboard the vessel and heading up the engine room.	[98]
First Engineer	Acts as an assistant to the Chief Engineer (above) regarding technical operations onboard the vessel and specific tasks delegated by the Chief Engineer.	[99]
Second Engineer	The supervision of the daily operations and the maintenance and upkeep of all machinery.	[100]
Third Engineer	Supervision of several systems, including the boilers, fuel, auxiliary engines, as well as condensate and feed systems.	[101]
Cadets (Deck and Engine)	A junior position, where the individual is undergoing training to understand deck officers' basic duties or engine room crew, respectively.	[102]
Master (Captain)	Provides directives for the upkeep, operation, and maintenance of the vessel's systems.	[103]
Chief Officer (Mate) C/M	Second in command to the Captain and manages deck duties as well as general maintenance.	[104]
Second Officer	A qualified OICNW watch stander, who manages and directs the bridge team in their navigational duties.	[105]
Other Crew Members	Responsible for the navigation and safe passage of the ship.	[106]
Owner or Organisation	Commonly known as the Operator, the individual or board in charge of general control and management of the vessel.	[107]
Shipping Agent (Passenger and Cargo)	The designated person or agency responsible for the handling of shipments and cargo as required.	[108]
Ship Charterers	An owner of a vessel who hires out the use of the craft.	[109]
IMO	A specialised agency under the banner of the United Nations. Responsible for guidelines protecting vessels in polar regions, as well as polar environments themselves.	[110]
Flag state control (FSC)	The state in which a vessel is registered.	[111]
Port State control (PSC)	The verification body in a national port undertake inspections of foreign vessels to ensure safe conditions.	[51]
Antarctic Climate Change and the Environment (ACCE Group).	Understanding of climate change across Antarctica and the Southern Ocean, and the impacts on the terrestrial and marine biota and ecosystems, builds on the material included in the Antarctic Climate Change and the Environment (ACCE) report, published by SCAR in 2009 (Turner et al. 2009), with an update of the key points in 2013 (Turner et al. 2014).	[54]

The Antarctic and the Southern Ocean regions face increasing demands for tourism activities, and several other activities also grow exponentially as well [112, 113]. The most common vessels undertaking an Antarctic voyage include fishing and cruise ships.

4.8 Conclusion

Thus, it may be concluded that, despite the hazardous conditions posed by the region, the Antarctic Peninsula is the most attractive tourist destination, with a yearly total of 322 trips made by a variety of vessels, while the Ross Sea is the most common destination for research vessels, resupply vessels and fishing vessels. Comparatively, South Georgia and the Weddle Sea are much less attractive to all sectors. The harsh physical conditions that the vessels have endured have been documented in this chapter. It has been found that the environmental conditions may not influence the characteristics of the subsurface formations. However, the delicate elements involved in the operation of the vessel could be adversely affected by both salinity and temperature. In the predefined areas 103 and 104, the Antarctic region’s salinity ranges between 33.8 ppt and 34.7 ppt. However, the Antarctic bottom water has a salinity of 34.7 ppt at a temperature of -0.4 ^{o}C. In comparison, the Antarctic circumpolar water has a salinity of 34.6-34.7 ppt at a temperature of 0.0-2.0 ^{o}C.

Chapter 5: Critique of Polar Code for the Operation of Vessels in the Antarctic

5.1 Introduction

The operation of vessels within the Antarctic region has been improved over years of ongoing research, resulting in safer passage through the hostile and inhospitable polar environment. In turn, it has to promote increased scientific activity and discovery. While polar voyages are certainly safer because of ice breakers, accidents still occur as a result of either equipment failure or human error, or a combination of both. This chapter provides a detailed revision of icebreakers sailing under the Australian national flag. It includes both the past and present status of all Australian ARVs, as well as critiquing the polar code method developed by DNV regarding the operation of vessels in the Antarctic region [114, 115].

The objectives of this chapter include being the first to identify the critical components which are negatively affected by low-temperatures and icing conditions, as well as demonstrating the application of the polar code in regard to safety functions, as well as inherent safety techniques for the installation of both machinery space and auxiliary machinery.

The above objectives can be achieved through:

- A review into DNV's classification of vessels undergoing winterisation, which applies to all stages of the commission, design, construction, and operation;
- An evaluation of the guidelines that are established as part of the polar code, as well as all additional requirements regarding the structural integrity of the hull and machinery space;
- A review into the statutory navigation requirements for polar vessels [116];
- A description, including technical details, of the Seawater Cooling System (SWCS) and the Seawater Central Cooling System (SWCCS);
- The use of the Failure Mode and the Effect Analysis (FMEA) [117] methodology in providing recommendations for the operation of the MV-Bluefin research vessel in polar climates;
- The analysis of the Seawater Central Cooling System Chest (SWCCSC) aboard the MV-Bluefin, and the identification of weak points; and
- An evaluation of the effects of winterisation on the SWCS.

As a result of operating in hostile polar environments, icebreakers face a number of unique risks, which the IMO aims to mitigate through the implementation of the polar code and all associated amendments. DNV supports all regulations and requirements associated with protective polar guidelines [114] and further develops the polar code to better suit particular flag state requirements. This is extended through the utilization of a number of associated guidelines, including SOLAS and MARPOL, both of which focus primarily on the hull material of the structure as well as auxiliary components and machinery space [114].

The guidelines for ARVs, as outlined by the DNV [114], reference navigation in the region, emergency procedures, the design and structure of the vessel, communication technology and equipment, as well as the management of various pollutants.

5.2 Systems affected by the harsh polar environment

Based on the literature that has addressed the winterisation of ship systems between 2014 and the present, most of the research conducted in the Arctic ocean regards the harsh environmental conditions and the resulting adverse effects on machinery installations. As such, this thesis aims to detail the worst effects of the environmental conditions that may affect the winterisation of vessels and subsequently provide recommendations for making contingency plans.

Table 9 provides an overview of the main and auxiliary machinery and equipment found aboard vessels that may be exposed to harsh climatic conditions, namely sub-zero temperatures and icing. Machinery installation is often divided into the main/propulsion and auxiliary engines, electrical generation, systems such as electrical, piping, refrigeration and air conditioning, firefighting and protection, deck machinery and cargo handling equipment, bow thrusters and stabilizers, instrumentations and control, safety equipment, and other auxiliary machinery and equipment. The auxiliary machinery may be in support of the machinery space for main propulsion engines systems and include heat exchangers and compressed air, deck equipment or cargo handlings such as propellers and shafting, steering gear and deck cranes, or in support of ship services such as ballast water arrangements and sewage systems (SS). The principal propulsion devices, including fixed pitch propellers, ducted propellers, podded propulsors, contra-rotating propeller, controllable pitch propellers, these components for ship systems are subjected to freezing and low air temperature in winterization.

Table 9: Major components and equipment affected by the harsh polar environment [115].

Object	Main Engine	Power generation	Emergency generation	Firefighting engine	Propulsion system	Steering gear	Bow-thruster
Turbocharger	✓	✓	✓	✓	×	×	×
Centrifugal pump	✓	✓	✓	✓	×	×	×
Oil pump/hydraulic pump	✓	✓	✓	✓	✓	✓	✓
Fuel pump	✓	✓	✓	✓	×	×	×
Air compressor	✓	✓	×	×	×	×	×
Electric Motors	✓	×	✓	✓	✓	×	✓
Seawater tank	✓	✓	✓	✓	✓	×	✓
Freshwater tank	✓	✓	✓	✓	✓	✓	✓
Sea chest	✓	✓	✓	✓	✓	✓	×
Water Cooling system	✓	✓	✓	✓	×	×	✓
heat exchangers	✓	✓	✓	✓	×	×	×
Refrigerator	✓	✓	✓	✓	×	×	×
Central air conditioning	✓	✓	✓	×	×	×	×
Electric cables	✓	✓	✓	✓	✓	✓	✓
Piping and fittings	✓	✓	✓	✓	✓	✓	✓
overboard discharge valves	✓	✓	✓	✓	×	×	×
LO and FO Purifiers	✓	✓	✓	✓	×		✓
Alarm & detection sensors	✓	✓	✓	✓	✓	✓	✓
Oil separators	✓	✓	✓	✓	✓	✓	✓

5.3 DNV Class Requirements Relating to Polar Vessels

The DNV society classification for polar code winterisation of vessels applies to all stages of the commission and use of polar vessels, including design, construction and operation (see Table 10) [114].

Table 10: DNV class requirements for the operation of vessels in polar regions [114].

Section	Requirements
A	As a general rule, both the structure of the vessel as a whole, as well as all components and machinery, are required to have the capacity to perform in the environment anticipated in polar regions. Table A1 displays the polar class notation and relates closely to nominal ice strength and thickness. The capacity of the vessel is ensured through the reinforcement of the hull against local ice loads, requiring that all sections of the hull be adequately strengthened according to the interaction of that segment with the surrounding ice. In localized sections of the overloaded hull in figure 4 [36], this reinforcement allows for minimal structural failure. Also, ships have specified the ice-reinforced areas of the vessel.
B	Sections of the vessel exposed to low-temperature seawater over extended periods of time are required to be constructed from either steel or pre-approved ductile material. The structural strength of the material can be classified according to the following four categories, which are dependent on both functions and anticipated loading. The wear-resistant coating is required on all external surfaces, which are ice-reinforced in an effort to prevent the abrasion of vessel components. According to Figure 4 depicts the steel grade for plating material located above the ballast waterline for the design temperatures of various categories. Forged or cast materials in structural members must pass impact and energy test, as shown in Sec.6 Table C1 item C1001 Table C1001[114].
C-F	Sections C through to F ensures the local and global strength, as well as icebreaking effectiveness, through the design and construction of the vessel and her components. It is a requirement that the bow of polar class vessels has the ability to break the ice in an effective and consistent manner, while maintaining continuous speed. The design of the bow should allow for the vessel to ride onto the ice, as well as include an ice knife allowing for the ramming of particularly thick ice, thereby avoiding excessive beaching of the vessel, as well as the submersion of the deck aft. The addition

Section	Requirements
	of the ice knife also allows for the distribution of broken ice across both the port and starboard, thus creating a navigable channel. Ice horns are also required to be fitted abaft each rudder for astern icebreaking, in an effort to protect the rudder within two degrees to each side of its mid-position and prevent the occurrence of wedging between the rudder and hull. The structural integrity of all equipment, substructures, and supporting structures cannot be negatively affected as a result of icebreaking accelerations. In order to calculate the loads encountered in various areas of the vessel, a number of equations have been developed, focussing primarily on the vertical force loads experienced by the bow, as well as the compression loads experienced by the amidships as a result of inward acting line loads due to the movement of ice floes. The aforementioned calculations allow for the assessment of longitudinal, transverse and fore ship strength. Pt.3 Ch.1 Sec.13[114] provides methods for checking the buckling strength of web plates and faceplates in girders/stringers that are subject to ice loads.
H	This section describes the minimum throat thicknesses for continuous double welds in structures with high shear and tensile stresses.
I	The mitigation of potential failure of systems and components is achieved through the implementation of removable hard and canvas covers, as well as the heating of pipes and cables. The design conditions of the components and mechanisms require that a surface temperature of at least 3°C is maintained. However, in situations where icing occurs, the use of hot water is recommended whilst considering and protecting all electrical components. It is also required that the design for the sea cooling water inlet and discharge take into account the potential blockage caused by ice. It is also a requirement that the cooling water tank volume is equal to >0.01 of the main and auxiliary engine output (kW), as well as all seawater cooling, pumps either connecting to a shared priming system or being able to self-prime. Ice separation and ventilation can be achieved through the arrangement and repurposing of a minimum of two sea chests as iceboxes. In an effort to mitigate situations where sea chests may be blocked, ballast piping allows for the circulation of cooling tank water through ballast tanks when spare cooling capacity is required. The ballast system is required to meet certain specifications in order to prevent freezing. In situations where the ambient temperature is 20°C colder than the design specifications, and the vessel is considered to be in a dead-ship condition, it is required that main machinery must restart after half an hour. As such, all ancillary and auxiliary machinery must have ice tolerant capabilities, as well as allow for ice-induced acceleration.
J, K	Azimuth and tunnel thrusters account for the main methods of propulsion. While tunnel thrusters require no ice strengthening, azimuth thrusters do encounter ice block strikes along the body, thereby requiring ice strengthening in order to withstand the loads incurred. As a general rule, all non-retractable thrusters require strengthening in areas where ice encounters are expected to occur, thereby resulting in special design considerations, including implementing a means for heating, as well as the circulation of hydraulic oil and lubricant. It is vital that the hydraulic oil maintains viscosity within an appropriate range in order to avoid freezing. While the performance of the vessel may be enhanced in polar conditions, the implementation of the aforementioned design features may reduce the engine output; however, this theory requires further testing. Propeller blades, propeller hub and blade bolts must have an elongation greater than 15% on a test piece of five times smaller diameter. An equation has been designed in order to calculate the minimum continuous output of propulsion machinery, which takes moulded breadth, polar class number, rule draught and stem angle into consideration.

5.4 Statutory Navigation Requirements for Polar Vessels

The polar vessels navigation requirements are a need for binding shipping regulations for the safety of navigation and protection of the Antarctic marine environment conditions. Related to the various maritime, geopolitical and legal issues raised by the IMO guidelines for ships operating in Antarctic ice-covered waters are analysed and discussed [114]. The IMO's mandatory regulations supplemented by various guidelines and nonmandatory codes or conventions are illustrated in Figure 27 [22].

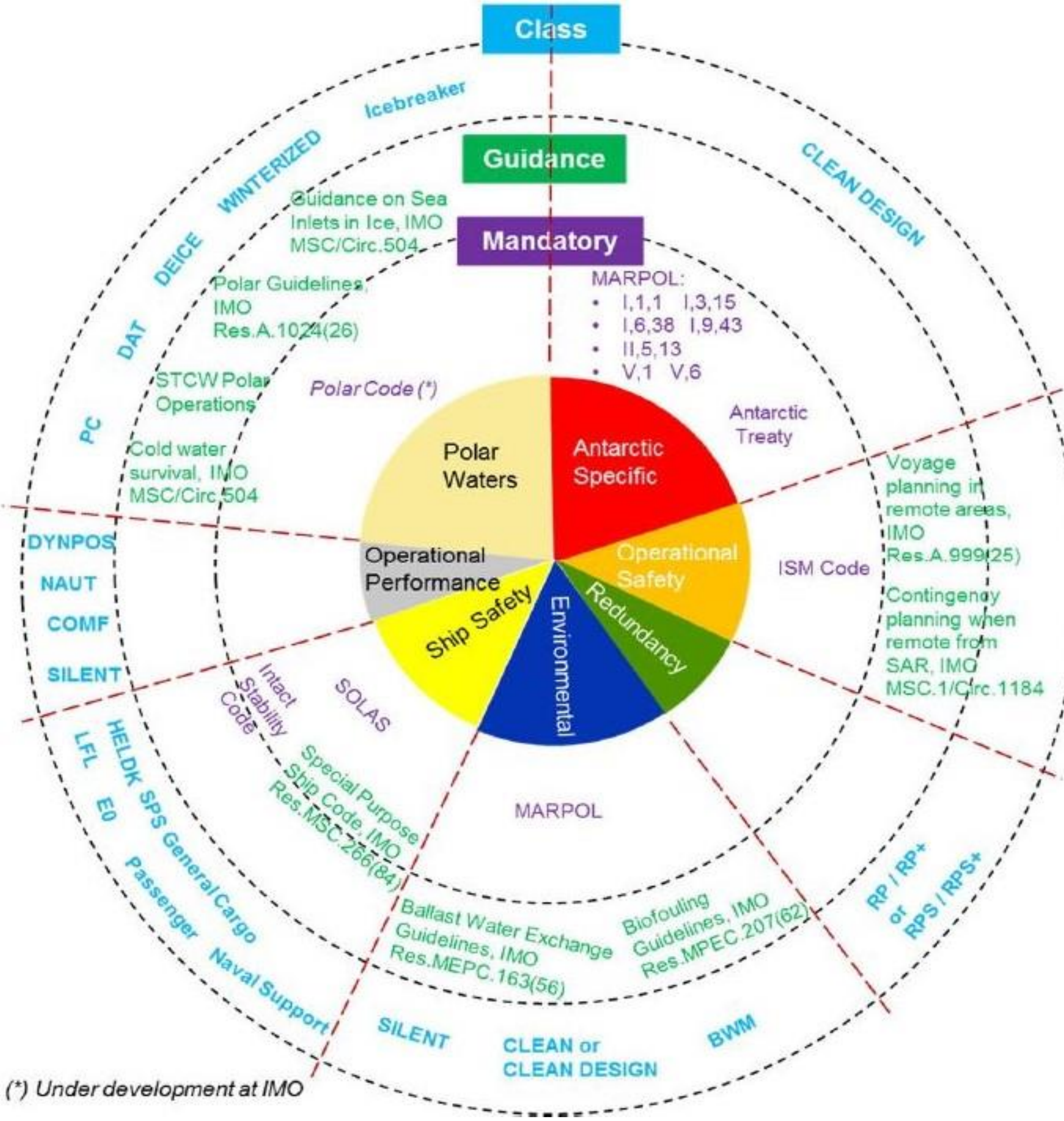

Figure 27: Winterization requirements for vessels operating in Antarctica.

Stability and Subdivision

- Waters, where both sea and land ice density is equal to <10%, are referred to as iceberg waters.
- A vessel with a high level of icebreaking capability, accompanying another vessel or vessels with lower icebreaking capability, is known as an escort.
- Any activity in which a vessel is accompanied by an escort is known as an escort operation.

- A well-ventilated environment, protected from inhospitable surrounding conditions, is known as a liveable environment.
- Any vessel whose operations include the escort of another, ice management, the undertaking of activity in ice-covered water, as well as providing a liveable environment is known as an icebreaker.
- The mark provided to a vessel by either a competent authority or organization that indicates the capacity to safely conduct navigation under sea ice conditions is known as an ice grade.
- The time frame for survival systems to give support is referred to as the maximum anticipated salvage time. This is not less than five days.
- All machinery, equipment, and associated piping and cables required for the safe operation of the vessel are known as mechanical equipment.
- The daily temperature lows over a period of ten years minimum are averaged to find the average daily low temperature. In cases where the data is insufficient, an average daily low temperature may be provided by a competent authority or organization.
- The polar code level means that the competent authority or the organization recognized by the competent authority complies with the uniform requirements of the IACS [14].
- Set below a daily low temperature of -10°C, the operating temperature specified by the design of polar vessels is known as the polar operating temperature.
- Vessel operating in regions where the daily low temperature is less than -10 °C are known as vessels intended to operate at low temperatures [114].

Stability Under Normal Conditions

- The side projection area of both sides of the ship above the water surface is 7.5kg /m^2.
- An exposed area of greater than or equal to 30 kg/m^2 of open deck and gangway.
- The total projected area of the continuous surface shall be increased by 5%, and the static moment of such area shall be increased by 10% for the calculation of the side projection area on the discontinuous surface of the ship without sails, various booms, masts (except masts) and rigging, as well as the side projection area of other small objects.

Stability Under Dangerous Conditions

- If the centre is located before the maximum width on the high ice zone waterline, the longitudinal range shall be 4.5% of the high ice zone waterline length. Otherwise, 1.5% of the increased ice zone waterline length shall be assumed to be at any longitudinal position along with the master.

- The full range of damage measured perpendicular to the hull's transverse penetration range is 760 mm.
- The vertical range is 20% of the high-water line draft in the ice area or the longitudinal range, whichever is smaller, and any upright position between the keel and the 120% high water line draft in the ice area shall be assumed [114].

Waterproofing Considerations

- The removal of accumulating snow and ice, particularly in high-traffic areas such as doors and hatches, is a safety requirement. As such, a means for removal shall be provided.
- In the case of a vessel operating in polar regions, it is required that measures be taken in an effort to prevent the freezing of hydraulic door or hatch systems.
- Any water- or weather-tight door or hatch not leading to or exiting from a habitable environment shall be operated by individuals wearing heavy winter clothing and heavy gloves, thereby requiring special design considerations.

Safety of Navigation

- All firefighting and safety equipment installed in the vessel's exposed areas are required to keep it free of ice and snow accumulation.
- All mechanical controls and equipment are required to be maintained to avoid the accumulation of snow and ice and be kept in a specified location at all times.
- All fire system protection equipment and systems require special design consideration to take into account the needs of individuals wearing heavy winter clothing and heavy mittens.
- The removal of accumulating snow and ice, particularly in high-traffic areas such as doors and hatches, is a safety requirement. As such, a means for removal shall be provided.
- The method of extinguishing a hazard may require special considerations, including the selection of a suitable medium.

Passage Plane

- Procedures required by the manual on the operation of polar waters.
- Any restrictions on hydrological data and available navigational aids.
- Available information on the extent and type of ice and icebergs expected near the route.
- Statistics on ice and temperature in previous years.
- Shelter.
- Current information on the density of marine mammals in known areas, including areas of seasonal migration, and measures to be taken when encountering marine mammals.

- Current information on relevant ship routing systems, speed recommendations and ship traffic services for known areas, including the density of marine mammals in seasonal migration areas.
- National and international protected areas on air routes.
- Operate in areas away from SAR facilities.

Prevention of Pollution

- The polar vessels navigation requirements shall be designed to reduce the possibility of polluting the Polar environment from oil pollution C807 Pollution prevention arrangements in table C1 and A4,5 polar are requirements for winterized notation to the protection of the Antarctic marine environment conditions.

Category (A) :

- All vessels built either on or subsequent to the first of January 2017, all fuel tanks of class A and class B ships with a total fuel loading capacity of less than 600m shall be separated from the hull shell at a distance of no less than 0.76m. This provision does not apply to small fuel tanks with a maximum capacity of no more than 30m.
- For vessels that fit into the aforementioned categories, as well as not being classified as oil carriers, all oil-containing cargo holds require separation at a distance of greater than 0.76m from the shell of the hull.
- For vessels that fit into the aforementioned categories although that weigh less than 5,000 deadweight tons require that all residual oil and oil tank bottom water be stored at a distance of greater than 0.76m from the shell of the hull. This provision, however, does not apply to small tanks with a maximum single capacity of no more than 30 m^3.

Category (B):

- The keel-laying stage, or similar, is referred to as construction.
- A floating sheet of ice of considerable thickness that is exposed to the coast from 2 to 50 m above sea level is known as an ice shelf.
- Any sea ice that has formed, and has fixed itself to the coast, as well as sea ice that is connected to the shore in the form of ice walls, ice cliffs, and shallow or grounded icebergs, is known as Fast ice does not move with currents and winds [118].

5.5 Recommendations and Checklist for the Winterization of Polar Vessels

Prior to the transit of a vessel to Antarctica and the Southern Ocean, the owner or organization is encouraged to review their winterization procedure, and ensure the following:

- Check the operation of both projectors and deck lighting.
- Check the operation of navigation equipment.
- Check the operation of communications equipment.
- Check the operation of clearing and heating systems of bridge windows.
- Check the operation of the respective whistle and horn heating systems.
- Check the operation of equipment heaters, including control equipment, electric motors, radar scanners, the reader gearbox, as well as in the steering gear room.
- Check the readiness of the lifeboat and davit.
- Check deck lines liable to freeze are drained dry.
- Check that a sufficient amount of salt, sand and equipment is on board the vessel for the expedition.
- Check the readiness of firefighting equipment and life-saving appliances, and that all safety equipment is protected from polar temperatures. Unless the interior of the lifeboat is heated, all portable water shall be placed in close by and heated compartments to prevent freezing.
- Check the steam supply and ensure that dead legs are drained in order to prevent freezing in polar temperatures.
- Check the operation of interior ventilation, reducing the interaction of freezing polar air coming into direct contact with equipment.
- Check the operation of steam injections and ensure that a switch occurs to the lower sea chest.
- Check the deck hydraulic systems, ensuring that they are free of moisture and water.
- It is recommended that regular checks and inspections of equipment take place.

5.6 Technical Details of Seawater Cooling System

Seawater Cooling System Background and Information

The SWCS is a fundamental system in that it allows for the removal of waste heat produced from the combustion process and is therefore required to withstand the hostile temperature of the polar regions, including the presence of ice.

The Seawater Cooling System

In order to cool the main engines, the flow and transport of a cooling medium being facilitated to draw heat away from the vessel's systems. The use of SWCS is entirely costless, although its destructive behaviour is highly problematic. As such, freshwater and lubricating oils are utilized to cool vital components of the main engine system. These are then cooled themselves by a separate seawater SW cooling system.

Figure 28 shows the typical Seawater Cooling Intake System (SWCIS), which consists of a lower suction valve to prevent air entry into the cooling system while the vessel is pitching and rolling. An upper valve is utilized to avoid sand or mud entry into the system while the vessel is either in port or in shallow waters. Connected to a sea chest, acting as an SW reservoir, the intake filters water to capture unwanted solids before entering the pump [119].

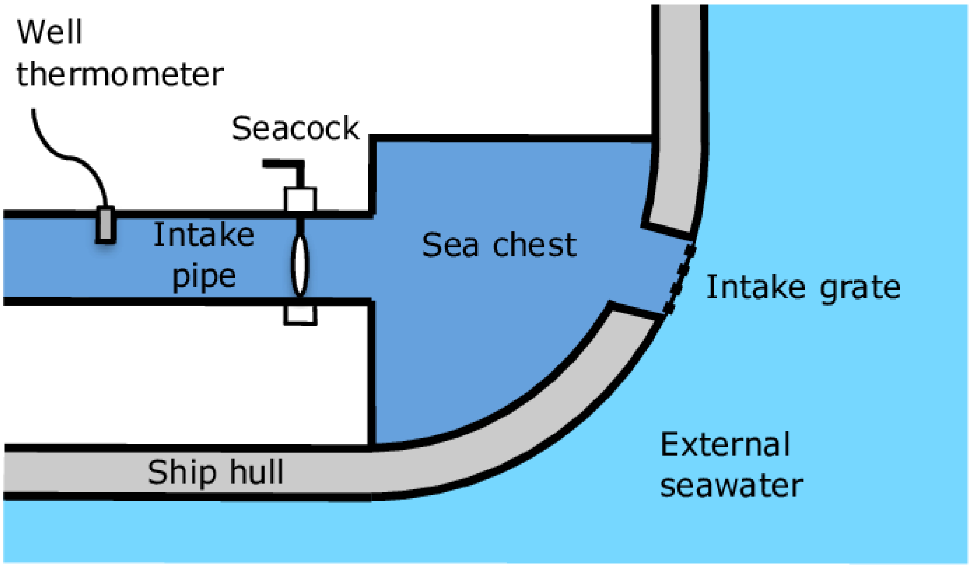

Figure 28: Seawater Cooling Intake System (SWCIS) diagram [120].

As the SWCIS enters through the pump, as seen above, the SWCS acts as a centralized cooling system. This can be seen in Figure 28, where seawater is fed through a number of coolers, including piston water, jacket water, lubricating oil, as well as line to the charge air if required.

Newer vessels consist of one large seawater cooler rather than a number of individual coolers as listed above. According to Figure 29, the seawater cooler cools an FW circuit and then goes on to cool the other coolers. This is known as the central cooling system and reduces the amount of machinery the seawater contacts, reducing the risk of problems with corrosion [119].

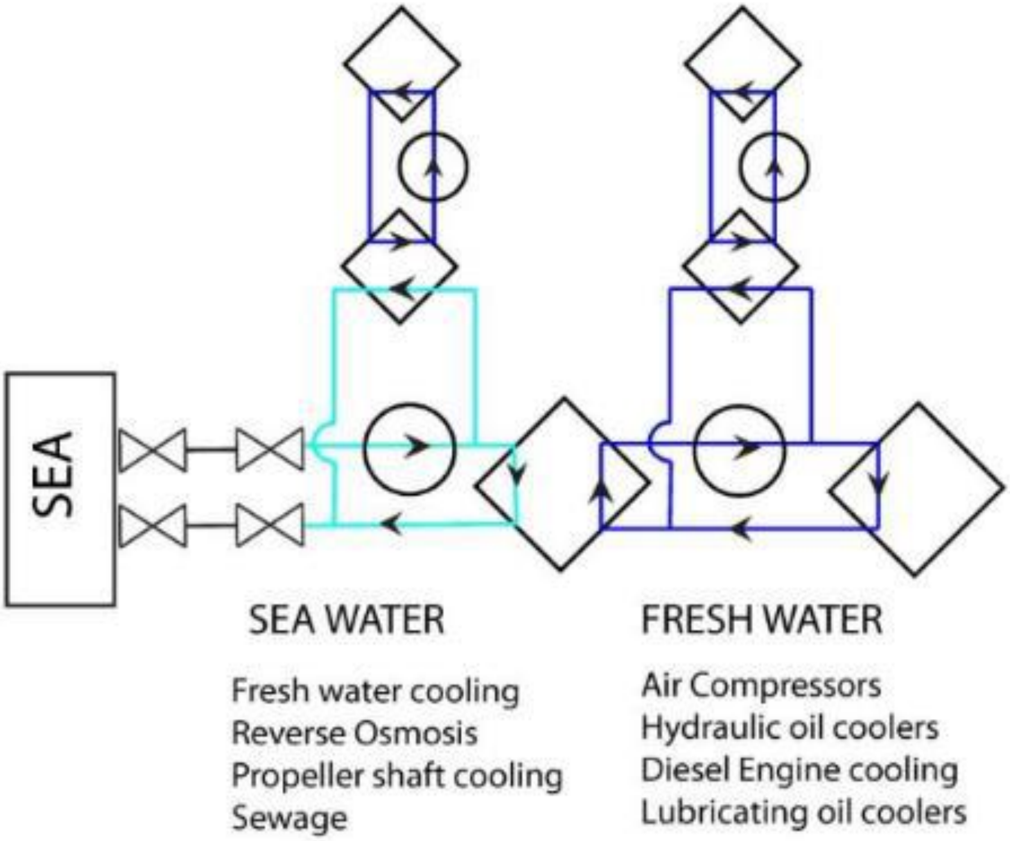

Figure 29: FW and SW centralised cooling system.

5.7 Description of a Seawater Central Cooling System

The Seawater Central Cooling System (SWCCS) can be seen in Figure 30. This type of system design has seen more frequently on polar vessels, components of which can be seen inTable 11. The SWCCS is an open-loop system, where the SW cooling pump, either sea cooling pump one (SCPP1) or sea cooling pump two (SCPP2), pumps water past the low-temperature FW cooler, either in service low-temperature FW cooler one (LTFWCL1) or low-temperature FW cooler two (LTFWCL2), absorbing the heat in the process. The heated SW is then discarded overboard, once leaving either in low service temperature FW cooler LTFWCL1 or in-service low-temperature FW cooler LTFWCL2. While passing through the system, all foreign matter is filtered from the SW through the sea chest strainers, the sea cooling pump 1 SCPP1 or sea cooling pump 2 SCPP2 strainers, and finally through the internal in-service low-temperature FW cooler LTFWCL1 or in-service low-temperature FW cooler LTFWCL2 strainers ISTR1 or ISTR2 [119]. The high sea chest (HSC) and the low sea chest (LSC) networks are kept below the SW line on the hull of the vessel, allowing for a continuous and gravity-powered fill-up of the cross-manifold.

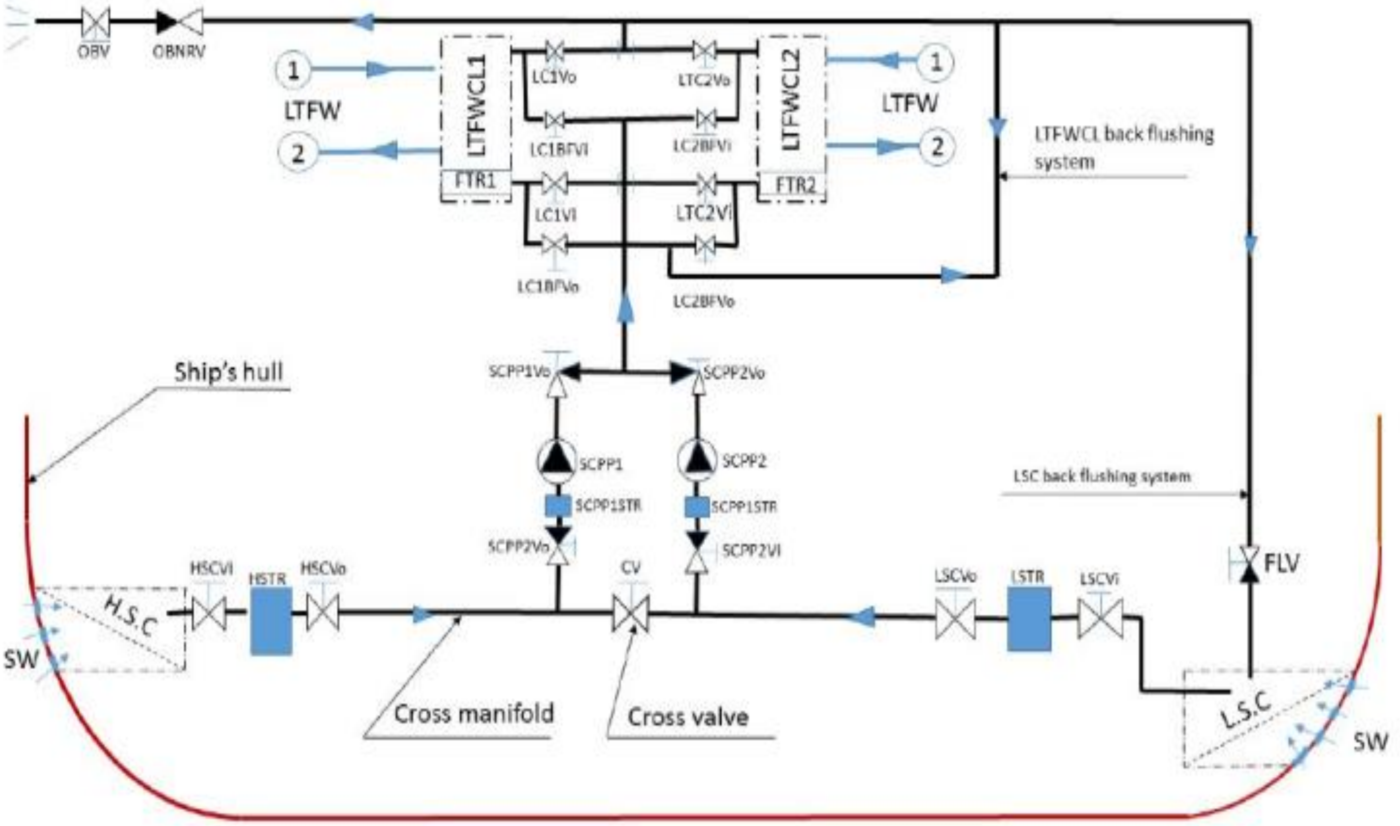

Figure 30: Centralised seawater cooling system chest [119].

Table 11: Components of the seawater central cooling system SWCCS, with Codes and Descriptions [119].

Codes	Descriptions	Codes	Descriptions
EJPP	Ejector pump	LTC1Vo	LTFWCL1 outlet valve
EJPPVi	EJPP pump inlet	LTC1BFVi	LTFWCL1 Backflushing inlet valve
EJPPVo	EJPP outlet valve	LTC1BFVo	LTFWCL1 Backflushing outlet valve
EJPPSTR	EJPP strainer	LTFWCL2	Low-temperature FW cooler 2
GSPP	General service pump	LTC2Vi	LTFWCL2 inlet valve
GSPPVi	GSPP inlet valve	LTC2Vo	LTFWCL2 outlet valve
GSPPVo	GSPP outlet valve	LTC2BFVi	LTFWCL2 back flush inlet valve
GSPPSTR	GSPP strainer	LTC2BFVo	LTFWCL2 backflush outlet valve
HSCS	High sea chest starboard	OBNRV	Non-return overboard valve
HSCSVi	HSCS inlet valve	OBV	Overboard valve
HSCSVo	HSCS outlet valve	SCPP1	Sea cooling pump 1
HSCSBFLV	HSCS back flush valve	SCPPVi	SCPP1 inlet valve
HSCP	High sea chest port side	SCPP	SCPP1 outlet valve
HSCPVi	HSCP inlet valve	SCPP1STR	SCPP1 strainer
HSCPVo	HSCP outlet valve	LSCSBFLV	LSCS backflushing valve
HSCPBFLV	HSCP backflushing valve	LTFWCL1	Low-temperature FW cooler 1
LSCP	Low sea chest port side	LTC1Vi	LTFWCL1 inlet valve
LSCPVi	LSCP inlet valve	SCPP2	Sea cooling pump2
LSCPVo	LSCP outlet valve	SCPP2Vi	SCPP2intlet valve
LSCPBFLV	LSCP backflush valve	SCPP2Vo	SCPP2outlet valve
LSCS	Low sea chest starboard	SCPP2STR	SCPP2 strainer
LSCSVi	LSCS inlet valve	SW	Seawater
LSCSVo	LSCS outlet valve	V1-V2-V3-V4-V5	Interconnection valve

The low-temperature freshwater (LTFW), which is not subject to our study, works in a closed-loop [119] and is cooled in the service LTFWCL1 or service LTFWCL2 before being passed through a number of different components and absorbing the unwanted heat, thereby allowing for the systems to operate within the design thresholds, and then back to the low service temperature FW LTFWCL1 or in the low service temperature FW LTFWCL2 to be cooled down. Valves are fitted at the inlet and outlet of each system's component to isolate it in case of routine maintenance. In the case of dirty SW, i.e. in port, or the river, it happens that the sea chests grids might be clogged. The backflushing system might resolve the problem temporarily of sea chest clogging by pushing back to the sea the dirt and foreign matters, waiting for a final cleaning by a diver.

The operation of an autonomous ship, for example, must operate without failure for a minimum period of 500 hours, or 21 days, without any external human intervention. Crew interference may only occur whilst undertaking repairs or when arriving at the harbour [119]. It is vital to identify potential risks, their root causes, as well as any failures modes to perform an adequate system improvement. The failure modes and effects analysis methodology (FMEA) has been identified by many experts in the literature supporting the vessel's system.

5.8 Selecting the Methodology for MV-Bluefin Research Vessel the SWCCS

When applying the FMEA method to the MV-Bluefin Research Vessel, SWCCS is selected as a part of the marine machinery risk assessment. It can be applied to each component of the system, thereby allowing for the systematic identification of potential failure modes, causes, and impact and allowing for the proposal of a preventative solution.

Table 12 presents the FMEA of the SWCCS. At the same time, Figure 30 identifies and demonstrates the potential faults of the system’s components as a result of the polar weather conditions and tracing root causes and assessing their effects on the operation of the vessel's system. This is to identify consequences ahead of time and avoid failure, a method is known as early failure detection, thereby improving the reliability of the design. Future work includes the adoption of intelligent condition-based maintenance (CBM) techniques and ensuring good repair practice, and enhancing the skills of the crew members to mitigate failure mode for systems.

Table 12: Conventional MV-Bluefin research vessel SWCCS FMEA [119].

Items	Designation	Failure Mode	Failure Causes	Failure Effects	Preventative Measures	Detection Approach	Recommendations
1	Seawater Cooling Pumps (SCPP)	1.Outlet SW pressure drop 2.Abnormal vibration 3. Abnormal overheat 4. Abnormal noise 5. Leakage 6.Corrosion	Pump: Impeller damage Shaft damage Mechanical seal Bearing damage Casing damage Running in dry condition Design faults Material incompatibility Human error Coupling: Coupling flanges damage Elastic coupling damage Coupling fingers damage Misalignment Driver: Electric failure Poor electric connection Low winding insulation Control system failure	FW LT cooling temp increase. Abnormal vibration Abnormal noise Stoppage of the main engine Blackout Maritime accident	Intelligent CBM. Good Working practice Use of original spare parts Qualified repair team Avoid overload Follow maker instruction Use suitable materials. Pre-heating of driver winding.	Vibration analysis Misalignment detection Pressure indicator and measuring sensors Dry running detection Temperature indicators and sensors Monitoring by infrared and daylight cameras	Training of repair and monitoring personnel. Enhance supervision and early detection devices Preventive maintenances -reliability improvement at the design stage
2	Low-temperature FW cooler (LTFWCL)	Pressure deferential increase Leakage corrosion	Clogging of cooler Damage of cooler due to overtightens Incompatibility of material Internal inlet filter clogged (FTR) Design faults Human error	Increase of FWLT temperature Stoppage of ME. Blackout Maritime accident	Intelligent CBM. Good working practice Qualified repair team Use of compatible material Tightens procedure per maker instructions.	Pressure indicators and transmitting sensors Temperature indicators and transmitting sensors Monitoring by infrared and daylight cameras	Reliability improvement at the design stage. Training and high Preventive maintenances for systems experiences. Maintenances renewal Monitoring the degree in low temperature for FW system.
3	High sea chest (HSC) and low sea chest (LSC) grids	SW pressure drop	Closing of the ship hull grids	Increase of FWLT temperature Stoppage of ME. Blackout Maritime accident	Backflushing Redundancy of sea chests. Use if the suitable HSC or LSC depending on draught and navigation area1.	Pressure indicators and transmitting sensors Monitoring by infrared and daylight cameras	Maintenance renewal and cleaning HSC and LSC as per timetable.
4	Valves	Frozen Corrosion Leakage V/V position fault 5. Opening and closing control failure	opening and closing control failure Incompatibility of materials. Human error	Depending on the location of the valve may lead to: Increase of FWLT temperature Stoppage of ME Blackout Maritime accident Engine room flooding.	Intelligent CBM Good working practice Use of original spare parts Qualified repair team Use of suitable valve and materials	Pressure and indicators and transmitting sensors. Monitoring by infrared and daylight cameras. Bilge level transmitter	Preventive maintenances for V/V Monitoring any leakage and corrosion
5	Piping	Leakage Corrosion clogging	Incompatibility of material The inefficiency of SW strainers. Damaged gaskets.	Depending on the piping branch may lead to:	Intelligent CBM Good working practice Qualified repair team	Pressure and indicators and transmitting sensors. Monitoring by infrared and	Preventive maintenances for piping Monitoring any leakage, explosion corrosion

Items	Designation	Failure Mode	Failure Causes	Failure Effects	Preventative Measures	Detection Approach	Recommendations
			Vibration due to poor or loosen piping supports. Incompatibility of piping dimensions. Human error	1. Increase of FWLT temperature 2. Stoppage of ME 3. Blackout Maritime accident	Use of suitable materials Engine room flooding	daylight cameras. Bilge level transmitter	
6	Transmitting sensors	Lecture error	Incompatibility of sensors. Poor electric connection. Over voltage. Human error.	Display error. Monitoring personnel wrong action. Disturbance of system functioning.	Intelligent CBM Good working practice Use of original spare parts Qualified repair team Use of suitable devices	Detection of devices faults detection	Monitoring the electric devices Preventive maintenances

5.9 Identified Weak Points of the MV-Bluefin Vessel Seawater Central Cooling System Chest

The system shown in Figure 30 presents a number of weaknesses of the MV-Bluefin's (SWCCSC) that render it unsuitable for installation. To enhance its appropriateness, a redesign is recommended, along with the implementation of a new general arrangement (GA) for the two seawater cooling pumps (SCCPP), where one is in use whilst the other is on standby. The connection to another available pump system onboard may enhance the redundancy without increasing the cost and reducing the engine space, such as the general service pump or the fire pump. The utilization of the same pipe for both SCCPP may result in unexpected issues, including icing and other environmental hazards resulting from the operation in a polar region. Damage to the solitary pipe may cause engine room flooding, which is why this paper recommends that a reconfiguration of the piping arrangement is necessary and required to avoid disasters whilst also providing cooling capabilities.

Another issue that may be encountered is the plugging of the sea chest due to ice or foreign materials that were not filtered from the water. This may be particularly true as a result of the harsh environmental conditions in the Southern Ocean and the particularly abundant biodiversity. As a result, it is recommended that both sea chests, and associated backflushing systems, should avoid running into or through another system.

5.10 Overview of the Heat Exchangers for the Cooling Water

The heat exchanger utilizes SW, which has been cooled, to reduce the other liquids' temperature (FW or LO) while remaining separate and not mixing with them. The heat exchanger can be differentiated into either shell, tube, or plate, as shown in Table 13. The shell and tube exchangers are illustrated in Figure 31, where fluid enters through the tube inlet and moves throughout the system. A second fluid enters the shell and remains separate from the first by flowing around the tubes rather than throughout. To maximize the fluid flow and cooling efficiency, baffles are used to redirect the shell inlet fluid and hold the tubes in place [121].

Table 13: Heat exchanger comparison [122].

	Plate Type	Shell and Tube Type
Advantages	1. Compact and simple design. 2. Efficient heat transfer. 3. Easy cleaning. 4. Dismantling requires no extra space. 5. The introduction of paired plates increases capacity. 6. Removal of leaking plates does not require replacement. 7. Simple maintenance procedures. 8. Deposits are reduced as a result of the turbulent flow, increasing heat transfer efficiency.	1. Cheap when compared to plate heat exchangers. 2. Allows for higher temperatures and pressures in the operation of the system. 3. The pressure drop across a tube cooler is less. 4. Ease of locating and remedying a leaking tube. 5. Tubular coolers in a refrigeration system can act as the receiver also. 6. The entire system is protected from erosion as a result of sacrificial anodes. 7. Tube coolers may be preferred for lubricating oil cooling because of the pressure differential.
Disadvantages	1. Initial costs are high due to the expense of titanium. 2. Pressure tests are not simple, increasing the difficulty in identifying a leak. 3. The operational temperature is limited by the bonding material between plates. 4. The pressure drop experienced is higher than that of the tube and shell cooler. 5. Dismantling and assembly are difficult. 6. An increased pressure drop results from over-tightening of the clamping bolts. 7. The operating conditions may lead to joint deterioration. 8. The cooling system is highly susceptible to corrosion, as titanium is a noble metal.	1. Lower heat transfer efficiency compared to plate coolers. 2. Difficult cleaning and maintenance. 3. The capacity cannot be increased, i.e. limited capacity. 4. Requires more space in comparison to plate coolers.

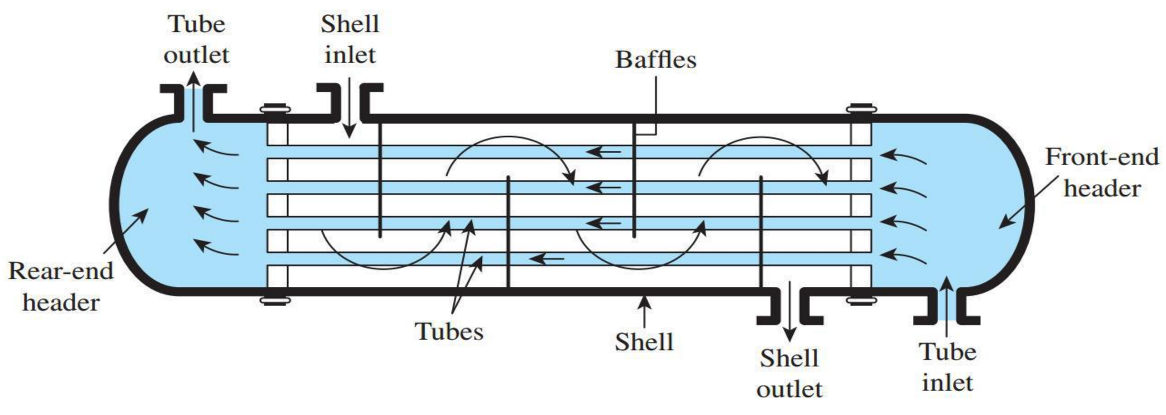

Figure 31: Shell and tube heat exchanger [121].

Alternatively, the plate cooler seen in Figure 32 circulates two fluids throughout a stack of stainless-steel or titanium plates, with rubber sealing alternating each fluid being able to run down the gap between plates. Strength and surface area are increased due to the corrugated plate design, thereby resulting in an efficient heat transfer.

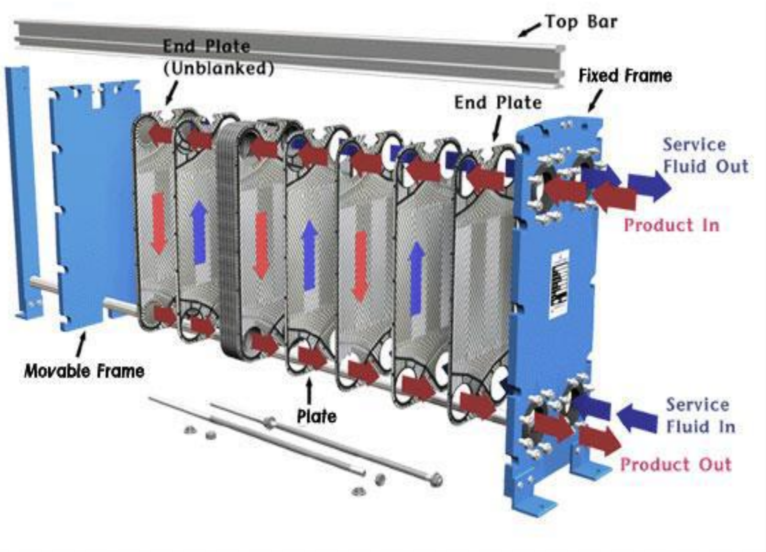

Figure 32: Inner workings of the plate heat exchanger [55].

5.11 Winterization of the SWCS

The intended work carried out in polar regions presents a number of unique challenges to the design of the vessel's systems, including the presence of ice and slush which may result in SW inlet and piping blockages with little to no warning. This is mitigated by placing SW inlets as close to the centreline as possible while also being as far aft and low as possible, thereby reducing the risk of ingesting ice, snow, or slush. This also requires that the high and low inlets be placed as far apart as possible.

The following design characteristics are required by sea bays and sea boxes:

- Reduce ice, snow, or slush ingestion with the implementation of a strainer plate at the inlet with 20 mm diameter perforations.
- Be as deeply emerged as possible.
- Locate both sea bays and boxes on either side of the ship, respectively.
- The suctions from the sea bay should equal 20% of the total open area to the sea.
- Clear sea inlets through the use of low-pressure steam or air system.
- Ensure that a vent with a cross-sectional area greater than or equal to the pipes is open to the atmosphere.

Ice blockages can be prevented further by implementing a vertical plate weir, which allows entering ice to float and thereby reduce the risk of ingestion through the strainer, described in Figure 33. This, however, does result in ice accumulation at the top of the tank, requiring a method and means of clearing it [123].

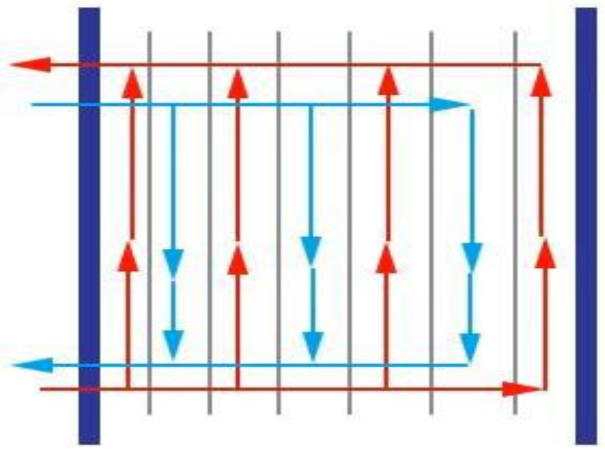

Figure 33: Principles of the plate heat exchanger [121].

As a result of the hostile environment of the polar regions, vessels that do not have the design specifications to operate in icy conditions will experience blockages in suctions systems as a result of supercooled SW freezing in pipes. As seen in Figure 34, polar vessels with specifically designed systems utilize heated SW, which is separated from the overboard discharge in the last stage of the seawater system to melt the accumulated ice that has blocked sea inlets and strainers, as well as to increase the water temperature in the sea box. As such, the entire system accounts for decreased SW temperatures allowing for the machinery to operate as efficiently as in other regions, avoiding mechanical failure [124].

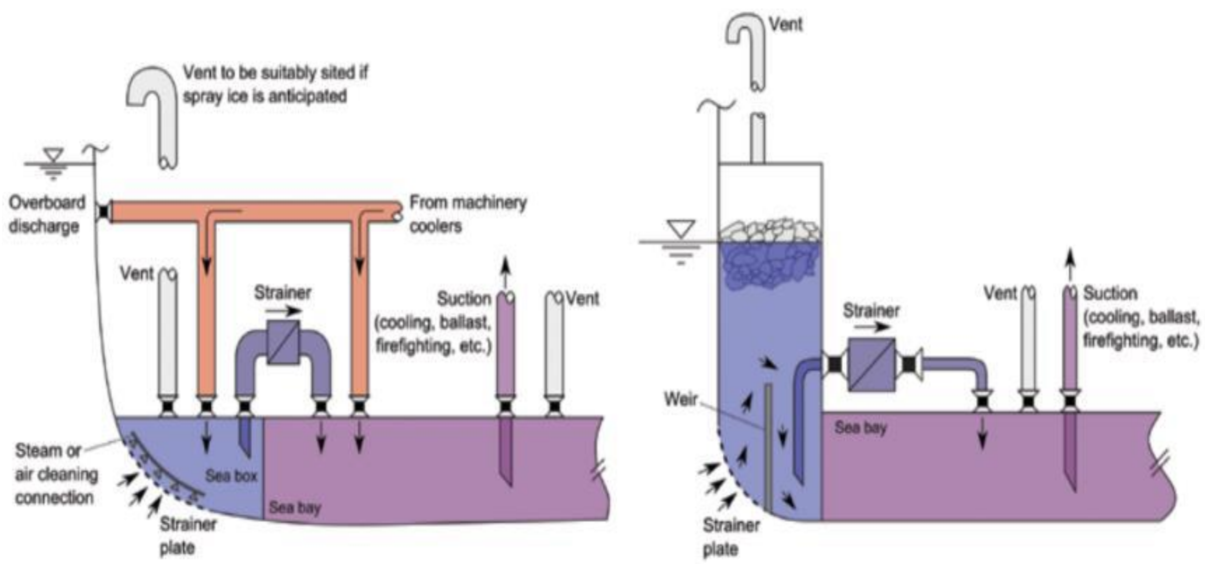

Figure 34: Winterization systems of polar vessels [125].

5.12 Conclusion

It may be concluded that the safety of polar vessels relies on the guidelines laid out in the polar code, including those related to construction, design, equipment, maintenance, and operations of the vessel as well as the overarching environmental protections. Such guidelines and regulations have allowed for human activity and ARVs in previously inaccessible, inhospitable, and hostile polar regions. While still undergoing development, the requirements outlined by all relevant and authoritative bodies have ensured that vessels operating in the polar areas are fit for their intended use, thereby reducing the rate of accidents or failures. This can be seen that all machinery installations must prove to be functional under a wide range of anticipated environmental conditions, including ice and snow accretion or accumulation, ice and snow ingestion from seawater, the increased viscosity of liquids as a result of various freezing stages, and the temperature of seawater intake that can be recommended for this study.

Chapter 6: MV- Bluefin Research Vessel: A Case Study for Operation in Polar Waters

6.1 Introduction

A number of design methods have been implemented into the structure and mechanics of polar vessels to achieve effective operation in inhospitable climate conditions. These design methodologies and the systems that they influence have been selected and created due to practical experiences in the polar regions [126]. The first winterisation notations were written and published by DNV and Lloyd's Register (LR) and issued in 2006. Thus, the classification societies' interest in the topic is considerably new sciences for keeping additional research in this field [126].

This chapter investigates the MV-Bluefin's capacity to transport passengers, operate in polar regions, demonstrate the heat tracing and insulation system, preserve or increase the temperature of the pipes. This was in an effort to evaluate the various winterisation systems best onboard the vessel and ensure their compliance with the polar code.

This will be achieved as part of the following objectives. The first objective is to provide an overview system of the MV-Bluefin research vessel to transport passengers to operate in polar waters. The second objective is to demonstrate the heat tracing and insulation system, aiming to preserve or raise the pipes' temperature and ultimately the vessel as the whole through heat tracing cables. The final objective is to investigate the winterisation process and justify the assessment of winterisation systems aboard the MV- Bluefin research vessel.

The above objectives can be achieved through:

- The evaluation of the critical equipment aboard the MV-Bluefin and their application to the polar code;
- A comparison of the vessel's specifications with the guidelines laid out in the polar code to determine whether the MV-Bluefin meets the requirements for winterisation;
- The identification and assessment of potential issues arising aboard the MV-Bluefin as a direct result of the hostile polar temperatures;
- The identification of the optimal SWCS for the winterisation requirements of the MV-Bluefin; and

- A review of the onboard systems whether they align with the polar code and other related guidelines.

In the past, all classification societies, such as ABS, DNV and Lloyd’s Register, have created individual thresholds for the definition of winterisation levels for the various systems utilised by polar vessels and recently implementing the polar code, which presents several guidelines regarding the operation of vessels in harsh polar conditions. A number of emerging vessel owners and operators aim to work in the regions surrounding the Antarctic and Arctic regions [126], however many lack sufficient experience for the safe and effective operation of vessels in the inhospitable and harsh polar conditions. As such, many vessel owners and operators rely heavily on the polar code and other such regulatory guidelines when making decisions on winterisation which should be developed for new buildings or the construction of a new vessel. A recognised difficulty in having a number of classification societies design and implement individual thresholds is that requirements vary, resulting in a lack of universal solutions when problems arise.

The major issue with the various winterisation notations and also to some extent with the polar code is that mostly they provide a current ship system to be winterised; however, very rarely offer a clear method in polar code on how to secure the operational capability in desired ambient environment conditions [126]. Further issues are caused by the definition of design such as structures, and machinery installation, ambient in low temperatures, and corresponding certification in low temperatures for the ship systems since the application of design in low temperatures under -30°C is the main effect on the availability and cost of various ship systems. This is especially the case when the designer temperature is set under -40°C.

The majority of winterisation thresholds and notations currently active are suited for polar vessels' operation in climates where the air temperature often falls below -30˚C. However, these vessels’ operation is often in open water, high seas areas, where sea spray's freezing causes issues for all the open-air mechanical structures and systems located on an open deck.

An alternative method exists for the assessment of winterisation impacts on polar vessels and the various systems onboard. This approach is practical, thereby creating suitable solutions for case-by-case situations in the polar regions, as demonstrated and justified in Tables 17-19. Previous versions of similar methods have existed, all with the same aim of basing the required level of winterisation for polar vessels on both designers and operators' prior experience. This process, governed by the principles of risk-based evaluation, stands to be standardised and streamlined, thus creating more clear reason-consequence pairing for the vessel's systems and operational requirements.

6.2 An Overview of the MV-Bluefin Research Vessel

The MV-Bluefin, certified for offshore operations and passengers' transport, is a 35m long domestic, commercial vessel operating as a research vessel. The vessel is currently supported at a fleet base, located near the mouth of the River Tamar at Beauty Point, Tasmania. Originally designed and built-in 1981, the MV-Bluefin doubled as both a coastal seafaring and fishing training vessel, demonstrating her flexibility and adaptability through modular mission systems and supporting marine science research and hydrographic surveys for mine countermeasures systems trials. She also provides opportunities for applied learning, taking onboard maritime engineers to conduct ship performance trials and design studies [127].

The majority of research vessels operating in polar regions are either ice breakers or ice-capable ships. The main purpose of this research is to collect old data of icebreaker and ice-capable research ships (greater than 500GT) from 2013 to 2019. These data were collected based on the literature review from different sources such as journal article, thesis, book, report and website and was validated. According to Figure 35 [22], DNV occupies the largest market share of icebreaker and ice-capable research vessels.

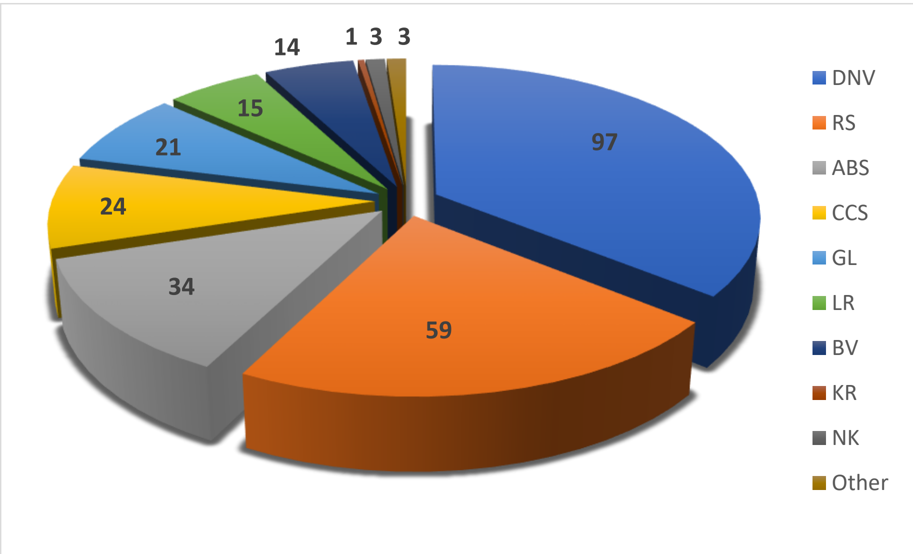

Figure 35: Market share of icebreaker and ice-capable research vessels owned by different society [22].

To select a suitable ice-class for the MV-Bluefin vessel operating in polar regions recommended by DNV, cold climate expertise has unique experience working in the polar areas with over 1,700 vessels with several ice-class notations represent above 30% of the DNV classed fleet. At present, DNV has in class up to 30 vessels with high ice class, including 19 ice breakers.

6.3 Recommended Ice Class Notations of the MV-Bluefin Research Vessel

DNV has developed several classifications that can be used to mitigate unwanted risks and several issues highlighted in this study. These classifications follow internationally recognised standard within the shipping community and ensure an individual ship is independently verified. DNV can issue statutory certificates for vessels operating in the Antarctic and may work on behalf of the flag administration. These notations/classifications are best summarised in Figure 36, which is best suited to vessels operating in Antarctica. According to the figure, the following notation would be recommended as a minimum requirement for the icebreakers operated by the Antarctica government.

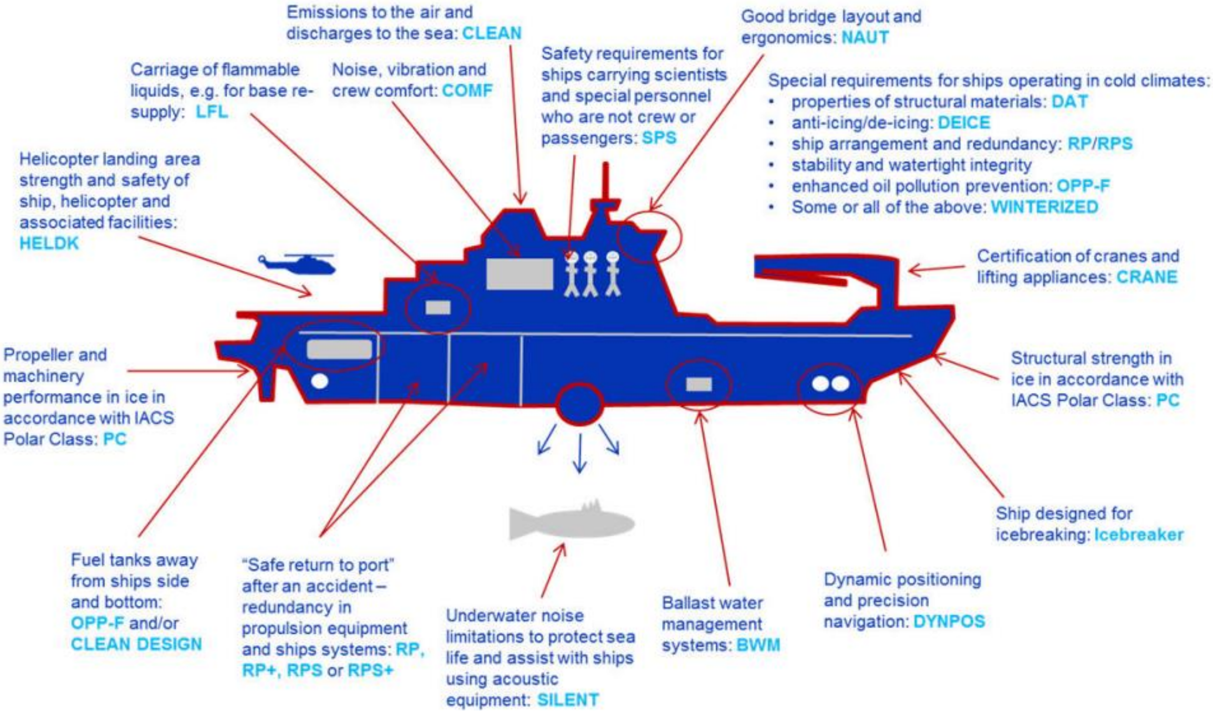

Figure 36: DNV Class notations that may be used to demonstrate that the risks of Antarctic operation have been accounted for and mitigated.

- **1A1 Icebreaker PC-3 WINTERISED COLD SPS COMF-V(2)C(2) HELDKSHF RPS DYNPOS-AUT NAUT-OSV(A) CLEAN DESIGN E0**

The polar class level (21) should be chosen based on the areas of navigation. For details, please see reference [128]. Classes 1 – 2 are better suited to Arctic operation with 3 – 5 for Antarctic operation in winter. For a summer resupply vessel, the following class notation is recommended as a minimum:

- **1A1 PC-7 WINTERISED BASIC SPS RP CLEAN DESIGN E0**

Full details of all the class notations can be found in Part 1, Chapter 2 of the DNV Rules for Classification of Ships [129].

Most nations send off resupply vessel to Antarctica during summer. During that time (November, January and February), ice conditions are reduced significantly. As a result, vessels with a lower ice capability are more often operated in Antarctica. However, there are some incidents of seeming trapped on ice by those vessels. For full-year access in this region, vessels with the capability in breaking thick ice are recommended. Sometimes Antarctic resupply vessels' are operational for alternate purposes, such as oceanographic research, geographical survey, patrolling, and security operations when not resupplying Antarctic bases. However, these multiple roles may conflict with another due to the vessel's specific design and requirements and could cause operation challenging. For instance, the balance between icebreaking capabilities and other open water tasks may create the most significant challenges, as illustrated in Figure 37.

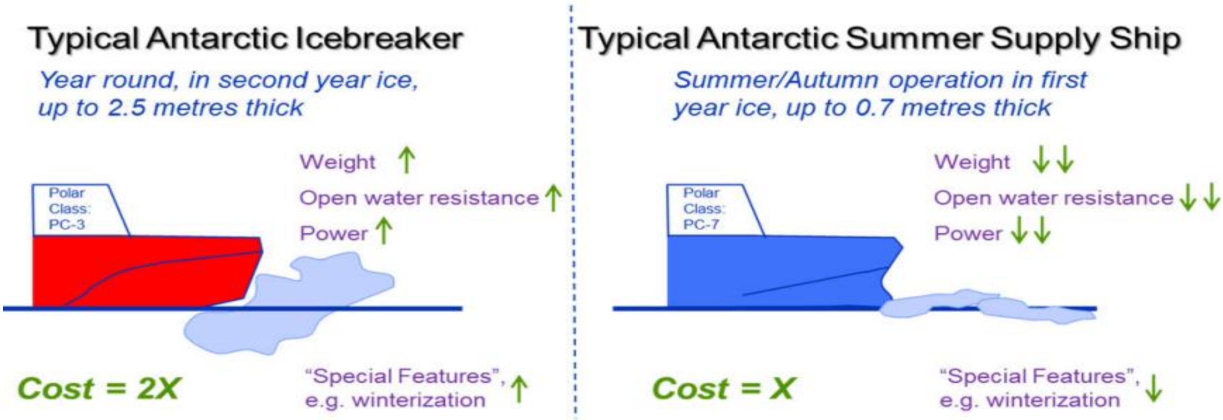

Figure 37: Trade-off between icebreaking and summer re-supply and survey.

Carrying a total of 25 members of crew and students combined, the MV-Bluefin conducts training sessions at sea, ranging between two days to two weeks. These applied learning voyages include habitat monitoring, fish stock sampling, fishing technology research, operation and maintenance of the engine room and associated machinery, undertaking environmental condition assessments, oceanographic instrument mooring lines, as well as ship design and function. The vessel also conducts training voyages for coastal masters, including training for pre-sea deck, integrated rating, as well as shipboard operations. The MV-Bluefin has also been chartered as part of the offshore industry through a number of maritime companies, for the purpose of underwater ROV pipeline work as well as hydrographic surveying [29], the rescue of stranded Antarctic scientists and crew, trials for minesweeping activity on behalf of the Royal Australian Navy, the survey of undersea cables located in the Bass Strait, as well as environmental surveys on behalf of a number of Australian marine organisations and also more information and specifications and requirements for the MV Bluefin Research Vessel shows in Table 14.

Table 14: Specifications and requirements for the MV Bluefin research vessel [127].

MAJOR DIMENSIONS Length OA 34.50 m Length BP 32.00 m Breadth 10.00 m Freeboard to Working Deck 1.20 m Maximum Draft 4.40 m Deadweight 53.60 t	ELECTRICAL DEVICES AND SYSTEM AC Voltage 415V, Total 96kVA 3 Phase 50 Hz. AC Voltage 415V, Total 96kVA 3 Phase 50 Hz. AC Voltage 24V, Total 30kW. Stabilisation of the system for effective use of scientific equipment. Voltage 240 VAC, Total 60 AMP 50.
DESIGN MATERIALS Hull Steel	RESEARCH FACILITIES Marine Biology Wet Lab 9 square metres Research Office, with computers and microscopes 10 square metres Sheltered deck space with work- tables
SPEED, ENDURANCE, AND OVERALL RANGE Range when Cruising 2,500 Nm Speed when Cruising 10.0 knots Maximum Speed 10.5 knots Endurance 15 Days	CAPACITIES AND WORKING SPACES Gross Tonnage 387 GRT No. 1, Dry Cargo Hold 4 cubic metres Fuel 46 cubic metres Fresh Water 30 cubic metres Ballast Water 20 cubic metres Total Area of Wet Laboratories 9 square metres Total Area of Dry Laboratories 10 square metres Fresh Fish Hold 5 cubic metres Frozen Fish Hold 3 cubic metres Free Working Deck Area 20 square metres Container Laboratory Space 6m x 6m
ACCOMMODATION Officers and Crew 5 People Scientists and Trainees 20 People Air Conditioned Accommodation is designed to cater for lecturers and students, ensuring comfortable accommodation in comparison to fishing vessels.	MAIN ENGINE Power (BHP) Caterpillar 850 HP at 1,200 rpm Diameter and Maximum rpm Propeller 2.20 m at 240 rpm Harbour and Emergency Set 180 KVA 2 x 80 KW Total Power Auxiliary Diesels are Excluded.
	ELECTRICAL SYSTEM AC Voltage /415V Total 96kVA 3 Phase 50 Hz AC Voltage /415V Total 96kVA 3 Phase 50 Hz DC Voltage 24V Total 30kW DC. Voltage 240 VAC Total 60 AMP 50 Hz Main Engine Caterpillar C4.4 Model DITA 129hp/93.6 kw at 1500rpm 24 volt Starting Fitted with fresh water cooled inter coolers Governor ECU (Electronic) Reduction Gear Ulstein Type 220 GSC Ratio 4.94 – 1 Controls Make MAR-EL No. 512

6.4 System Identification and Critical Equipment List

An evaluation of the winterisation efficiency for the systems and operations aboard the MV-Bluefin is required, which is achieved through the review of the general arrangement (GA) of the vessel, seen in Figures 38 and 39 also Table 15 [127]. Once the identification and evaluation of the MV-Bluefin systems and operations have been undertaken, as well as their respective location determined, it is possible to estimate the risk related to operational capabilities of the target systems in relation to defined environmental conditions. After defining the risk value, the initial design approach for the target can be selected. This selection is based on previous solutions, the operator's experience or a completely new solution. If the design is developed further, a more detailed evaluation of system cost and performance can be conducted further [127].

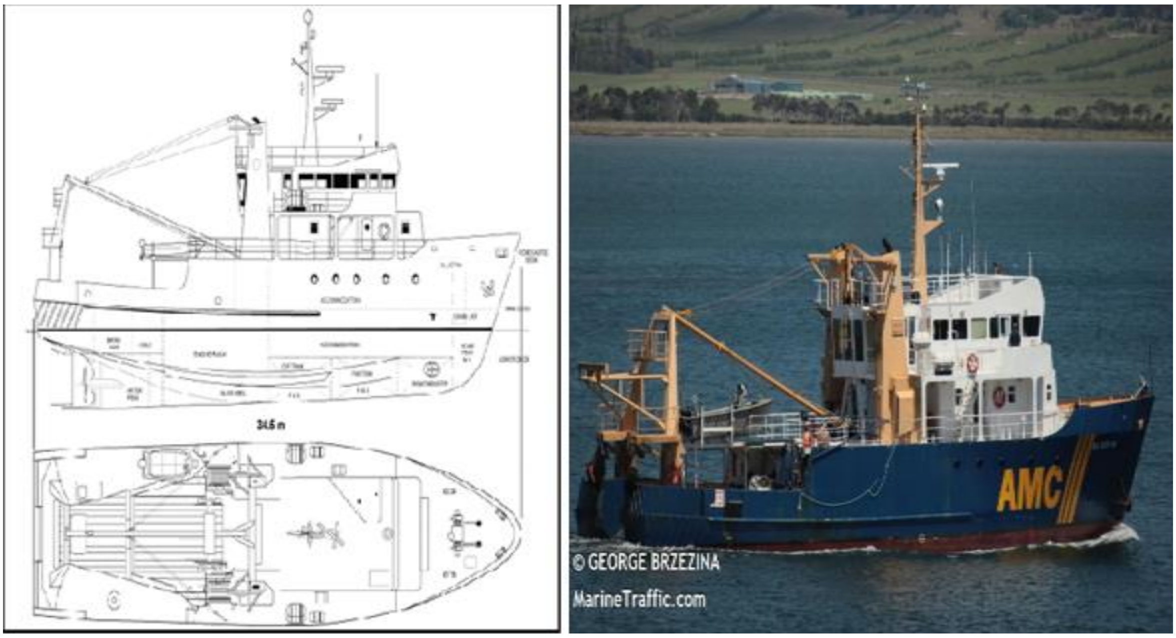

Figure 38: General arrangement of the MV-Bluefin vessel.

Machinery Systems

- Main Engine.
- Generators, Both 1 and 2.
- Electrical Distribution Board.
- Propulsion System.
- Main Steering Gear.
- Emergency Steering Gear.
- Bilge Pumps and System.

- Main and Emergency
  Fire Pump.
- Derrick.
- Fire Detection System.
- Windlass Cable
and Anchors.
  Fire Pump.
- Derrick.
- Fire Detection System.
- Windlass Cable
and Anchors.

Navigation Equipment

- Navigation Charts.
- Magnetic Compass.
- Radar.

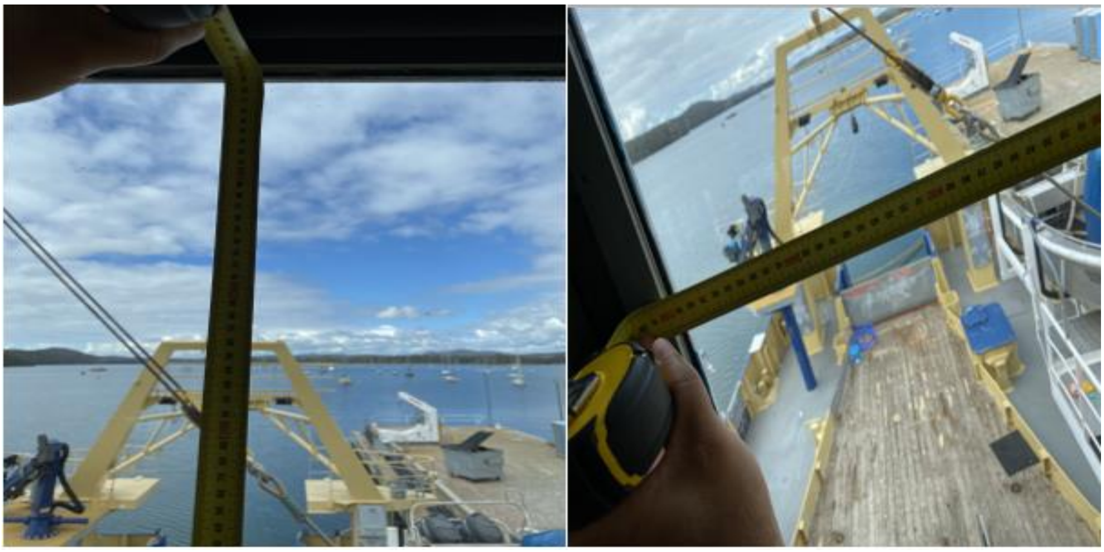

Figure 39: Measurement of the bridge winds as length, breadth, and size.

Emergency Response Equipment

- Firefighting Equipment.
- First Aid Equipment.
- A Range of Lifesaving Appliances.
- GMDSS Equipment and Emergency Power Supply.
- Workboat.

Table 15: Type of electronic hydraulic with automatic overload control.

Items (electronic hydraulic)	Automatic overload control
Propeller Make	Ulstein, Rotation RH
Model 4 Blade Diameter	2.2m Variable Pitch
Forward Power Take-Off Make	Twin Disc
Governor	Woodward Electronic
Generators	Leroy Somers, Model LSAM442S7, Power 86EKW, 107 KVCA, 3 Phases
Model SP 214 PM T1 Triple Output, Rating 38.5 HP/100 RPM	471.62/1,225 RPM
Auxiliary Engines	Caterpillar Electric Start 24V DC
Voltage Regulators	Genuas ayr 380
Model SBO	242
Controllers	Deep Sea Electronics, Model 8610 Auto Synchronise
An Excitation Support System	Basler
Over the Current and Revers Power Protection System	Genop-21

Manoeuvring and Propulsion

- C.P. Propeller
- Bow Thruster
- Bow Anchor, Anchor Cable Length: 150m

Steering Gear

- Wagner Electric Hydraulic Twin Ram
- Model T-15-35-EB2. Full follow up.
- Automatic Change Over to hand Steering in the Event of Power Loss
- Setting Relief Valve at 1,000PSI
- Balanced Rudder Type
- Angle 37 ½° or 75° total
- Hard over to hard time – 11/22 seconds

A model MAB-103B Alfa Laval Separator, assembled with a solid retaining bowl, was installed in 1985. This served a dual purpose; to maintain the clean and satisfactory condition of the hydraulic oil, as well as to remove all contaminant from the fuel. This assembly ensures the safe transfer of fuel at sea from the double-bottom tanks to the daily service tank, as well as circulating the fuel within individual tanks. The liquid contained in the separator bowl is subjected to an estimated 7,000 times the gravity on Earth.

6.5 MV-Bluefin's Main System Specifications

The MV-Bluefin consists of a number of systems, initially converted from the original fishing vessel to systems required by a research vessel, thereby reducing costs [127].

Cooling Seawater System Aboard the MV-Bluefin

As demonstrated in Figure 40, the cooling seawater system (CSWS) for the main and auxiliary engines is circulated through the Caterpillar engine driven. This applies to both the freshwater system FW and the seawater SW cooling system. The air-conditioning refrigeration plant condenser is seawater cooled using a Stalker centrifugal pump (CP) with a similar relief valve working at a pressure of 200 KPA.

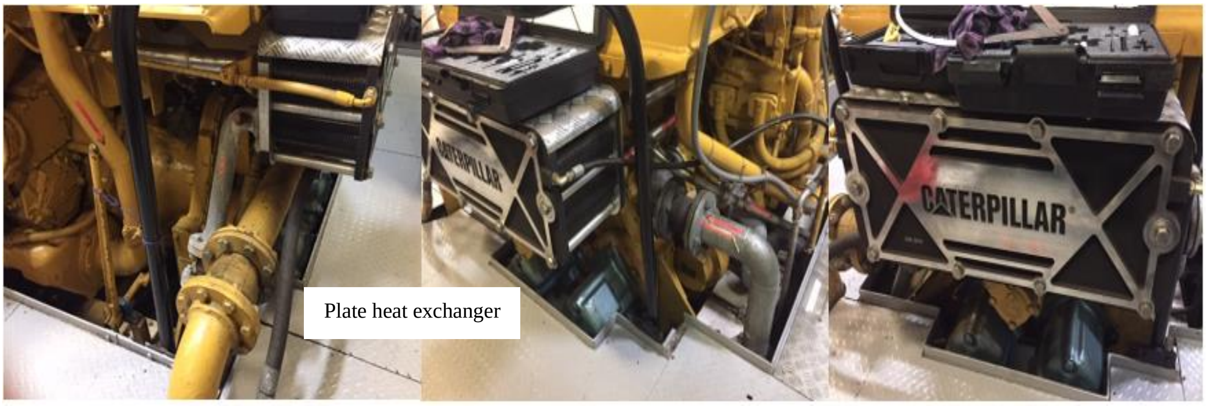

Figure 40: MV-Bluefin plate heat cooling system exchanger [127].

Freshwater System

Two double bottom tanks, as well as aft side tanks, make up the FW, weighing a total of 56 tonnes. The water is pumped from the respective tank into a pressure vessel, which is controlled by a pressure switch. The FW is distributed throughout the MV-Bluefin from the pressure storage through a filtering system, as seen in Figure 41.

Figure 41: FW hydrophone pump [127].

Sewage Pump System

The sewage pump system (SPS) found aboard the MV-Bluefin allows for water in the toilets. Situated in the engine room forward, as seen in Figure 42, the sewerage tank collects sullage water from the lower deck. From here, it is pumped into an Ecomar 6AC sewerage treatment unit, which includes an inbuilt macerator where the waste products are chemically treated. The Econmar unit is both Lloyd’s and IMO approved.

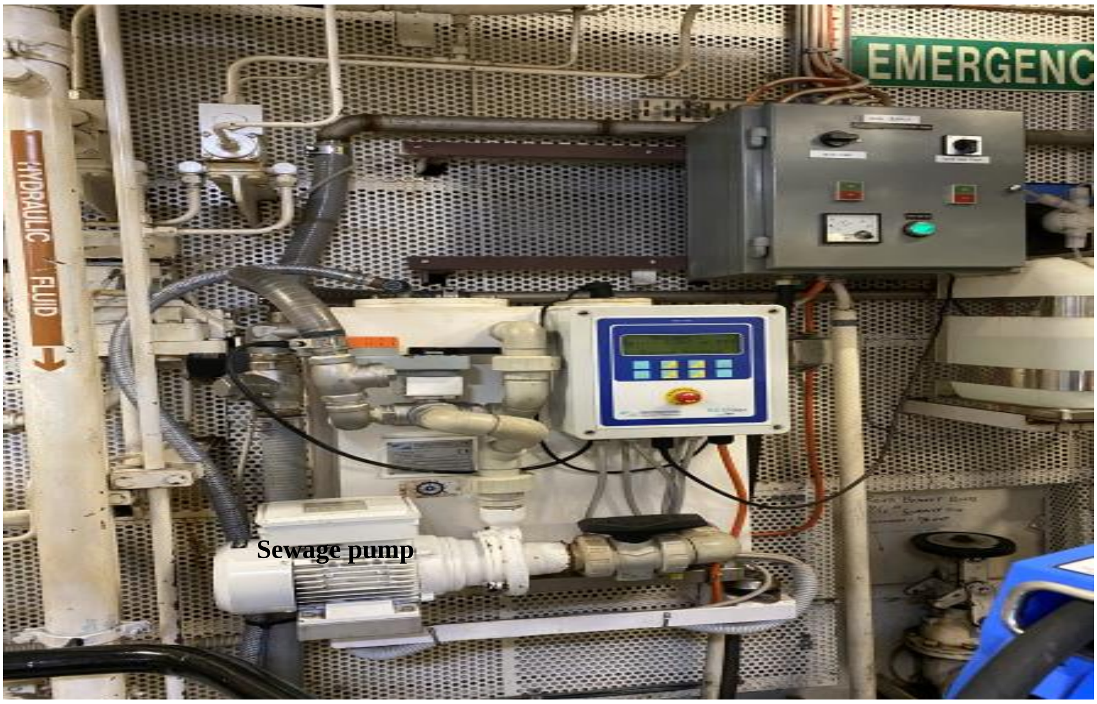

Figure 42: SPS aboard the MV-Bluefin [127].

Fire Main Pump (Water on Deck)

Manufactured by Kelly & Lewis and supplied by an electrically driven CP type of 1 ¼ -9, the fire main pump (FMP) draws saltwater from the main seawater, thereby feeding the main fire switch. Figure 43 demonstrates this, which doubles as a general service pump. An additional fire pump for the event of an emergency is powered by an independent diesel motor found in the steering flat. This doubles as a 3-cylinder self-priming Yanmar to Stalker pump.

Figure 43: Water on deck aboard the MV-Bluefin [127].

Bilge Pump System

Divided into a multitude of compartments, the MV-Bluefin is equipped with a bilge suction pipe that leads to a valve chest, ultimately all connecting to the bilge pump section chest. The chest utilises a sea injection valve for the purpose of priming, and the self-priming bilge pump is a model Pegson 2” B3 Kelly & Lewis. A dual-purpose exists in the pumping of water ballast from the aft peaks’ tanks, and all discharge is ejected overboard. This can be seen in Figure 44, which demonstrates the overhead storage bilge tank and ejected to a shore facility.

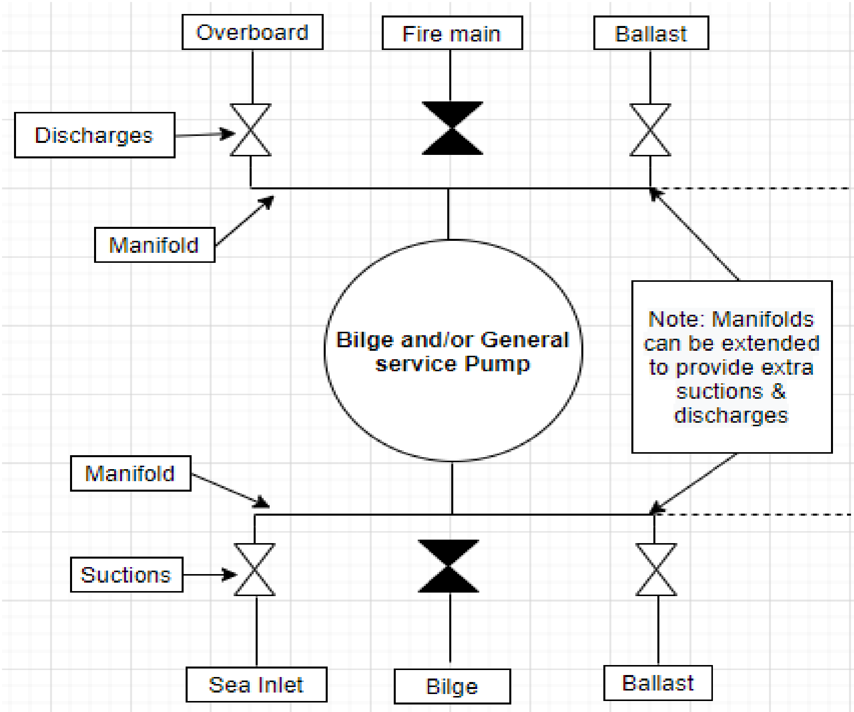

Figure 44: Bilge Pump System (BPS) aboard the MV-Bluefin [130].

Bilge Pump System Components

The BPS aboard the MV-Bluefin is designed to eject bilge water from vessel compartments, as listed in Table 16. The source of the aforementioned bilge comes in the form of leaks in the cooling system, hull, or stern tube glands [59]. Adjacent compartments must be kept dry by the BPS when the vessel's hull is filled with water.

Table 16: Standardised BPS components.

Component	Function
Pump	The self-priming bilge pump draws water from the bilge through suction and ejects it at sea.
Pipes	All pipes are required to be constructed from a material that is not adversely affected by foreign materials, including fuel and oil. These pipes allow for the transport of bilge water through the BPS.
Strainers	Strainers prohibit the contamination of the bilge pump.
Bilge Pump Level Alarm	Should the bilge water level in the pump exceed a certain level, the alarm sounds.
Discharge with Non-Return Valves	Bilgewater is ejected out to sea through the non-return valves which stop seawater from entering the vessel.
Suction Non-Return Valves	The transport of water between compartments in the vessel requires non-return valves to prevent back flooding.

Fish Handling Room

Branching from the fire main, seawater is supplied for the washing down and cleaning of the fish handing room and fish fillets. The handling room has a large drainage sump on the starboard side fitted with a float switch and a high-level alarm. The float switch controls a CD 60 mono pump situated in the engine room, which pumps the sump contents overboard as required [127].

Seawater Cooling System Modification for MV-Bluefin Winterisation

Drawn from the seawater main and pumped into a low-temperature pressure vessel, the Seawater Cooling System Modification (SWCSM), controlled by a pressure switch, as seen in Figure 45. The water is pumped from storage tanks into the vessel's internal systems for cooling as well as a variety of other systems, including the toilet and wash deck systems [127].

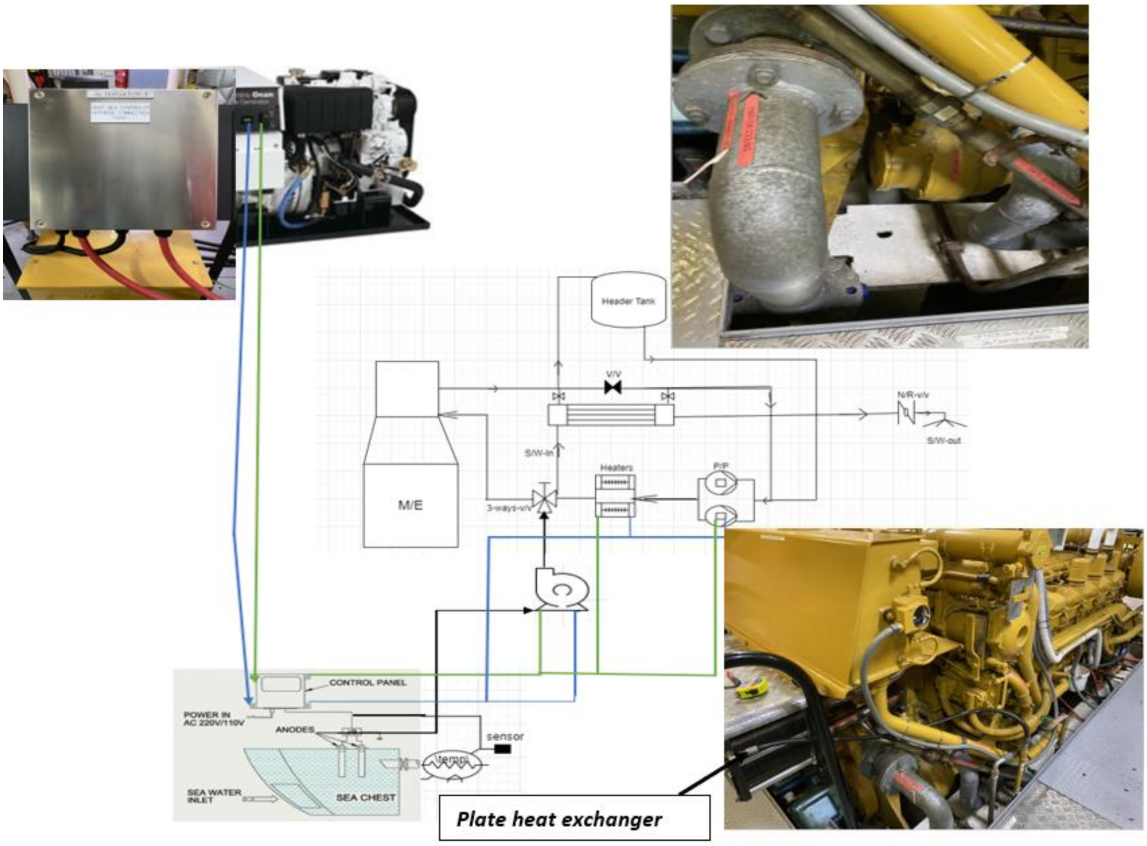

Figure 45: Components of the SWCS aboard the MV-Bluefin when preparing for winterisation.

Sewage System Modification for MV-Bluefin Winterisation

Drawn from the SW main and pumped through the low-temperature pressure vessel, the SS is controlled by the pressure switch, as seen in Figure 46. Water is pumped from the storage tank into the vessel's internal systems.

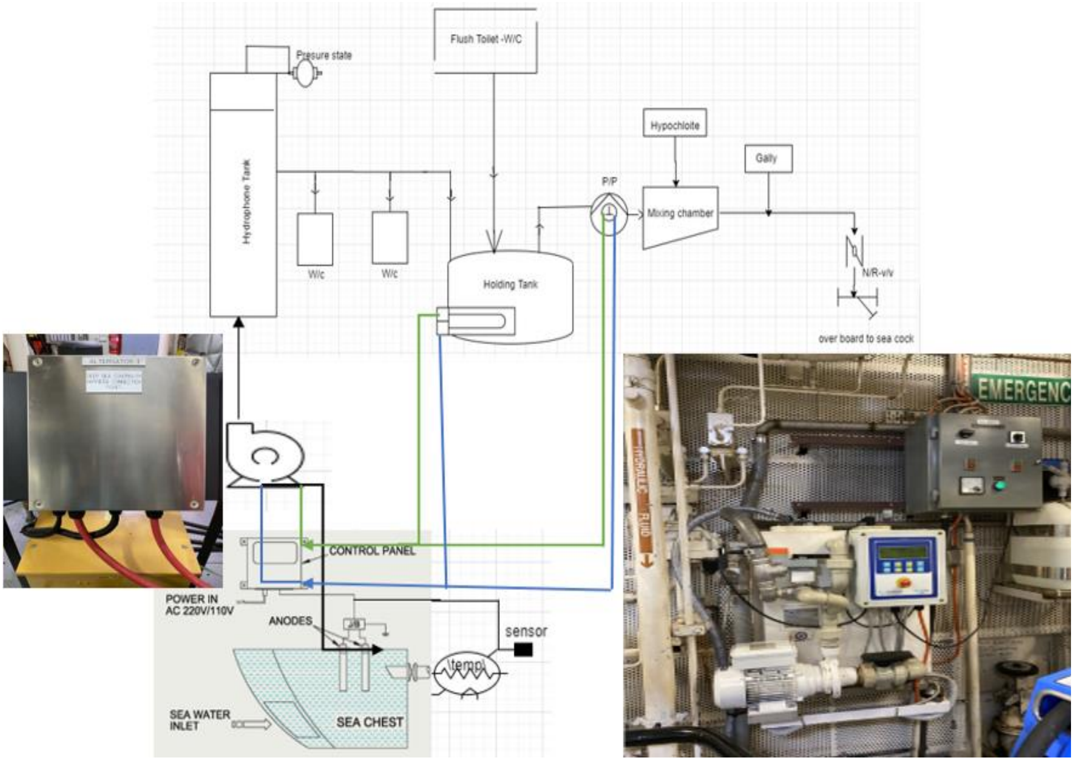

Figure 46: Sewage system modification for the MV-Bluefin.

The propulsion system aboard the MV-Bluefin consists of the following components: The main engine, a driving device, a marine shaft, and a propeller in Figure 47. The engine provides the impulse behind the marine propulsion system, while the driving device connects and transfers the energy emitted from the main engine to the shaft, which parts the energy to the propeller. The vessel is, therefore, able to sail [131].

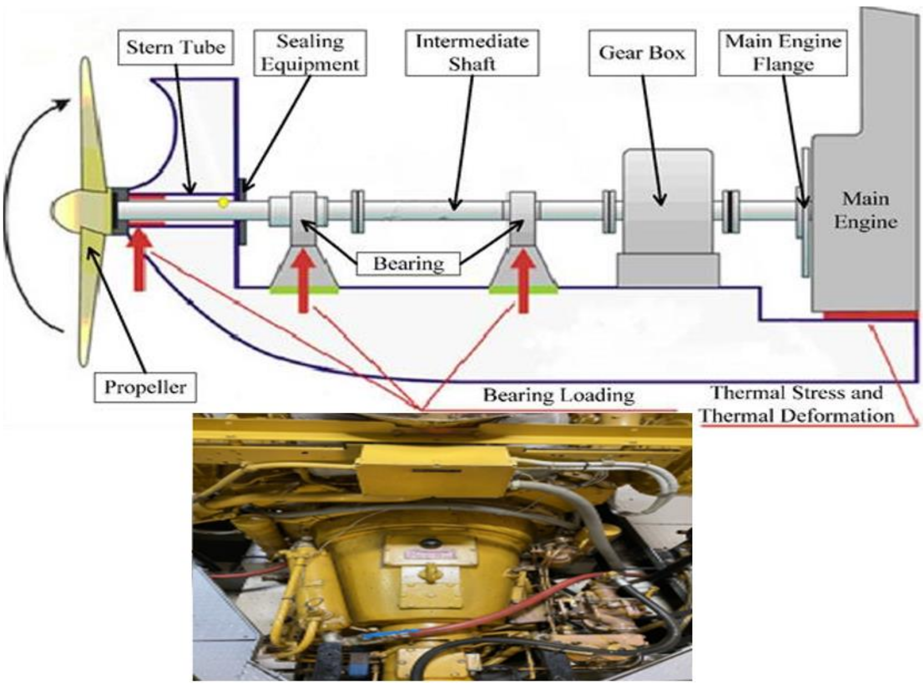

Figure 47: MV-Bluefin propulsion system [131].

Fuel Oil System

The fuel oil system (FOS) aboard the MV-Bluefin, shown in Figure 48, consists of two distinct segments: the fuel supply and injection systems, respectively. The provision of fuel oil is achieved through the fuel supply system, which receives and stores fuel before delivering it to settling tanks. This supply system consists of bunkering, storage, transfer, offloading, and treatment. Fuel oils are loaded through deck fill connections that have sample connections provided to permit the fuel to be sampled a bit taken aboard. Heavy fuel oil is loaded in storage tanks fitted with heating coils [33].

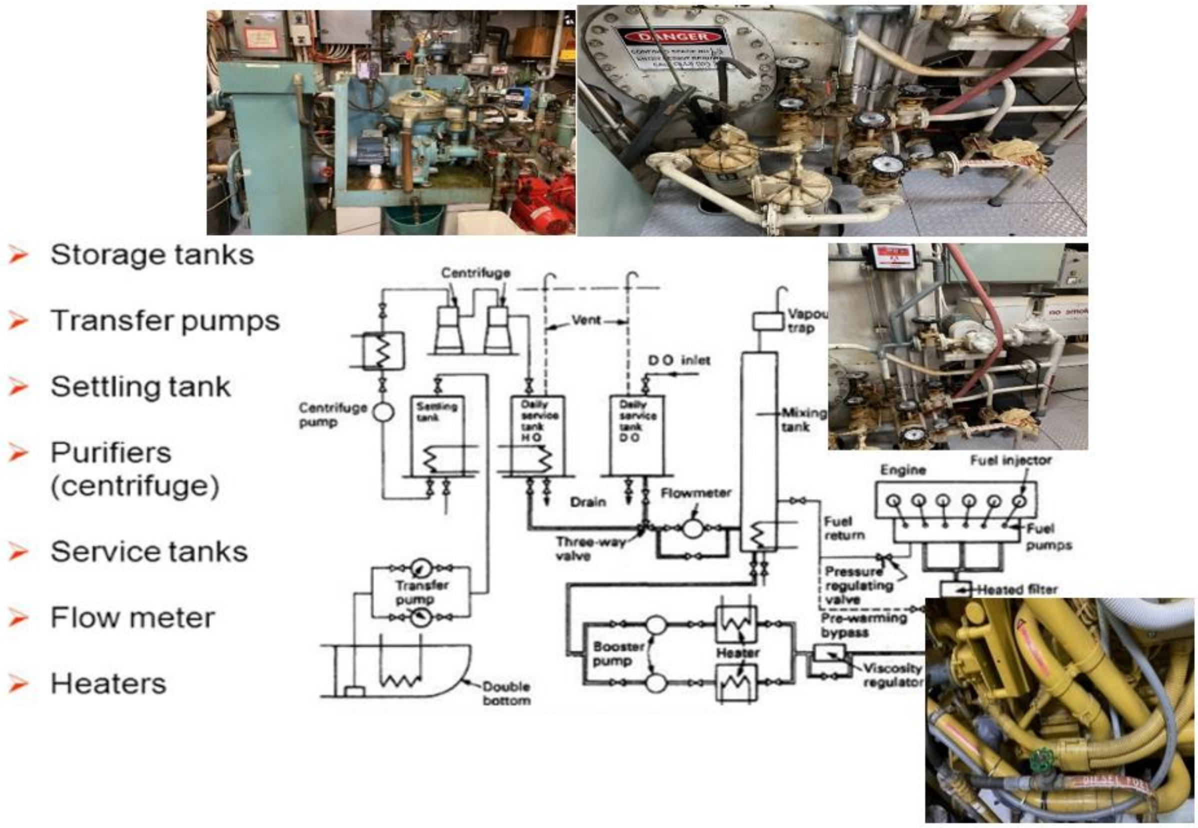

Figure 48: MV-Bluefin FOS components [33].

Lubrication of Oil System

Below the sump, otherwise known as the drain tank, the lubrication oil system (LOS) is stored at the base of the crankcase in Figure 49. The oil stored in this system, used to feed the engine, is drawn through a number of stages: a Strine, a pump, a fine filter, and finally passed through a cooler prior to being distributed through the engine and into various branch pipes. The oil originating from the lubrication system will pass through a drilled passage into the crankshaft and finally pass from a drilled passage into the connecting rod to the gudgeon pin or crosshead bearing [132]. The oil cooler is circulated by seawater, which will be operating at low temperature, and the oil will be affected base on that, which is at a lower pressure than the oil.

As a result, any leak in the cooler will mean a loss of oil and not contaminate the oil by seawater [132]. Special attention is made to this critical system to ensure that it is operating safely to avoid the system's failure.

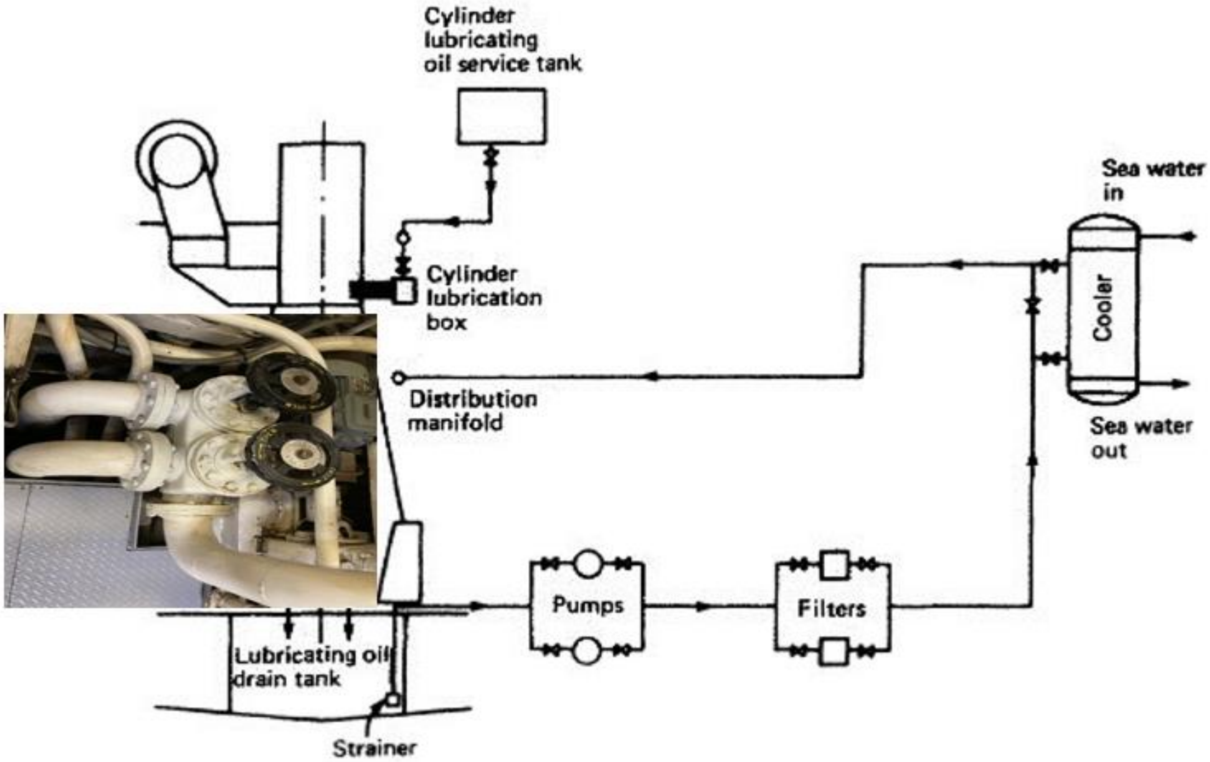

Figure 49: LOS aboard the MV-Bluefin [132].

6.6 Comparison of the MV Bluefin Systems with the Polar Code Methodology and Guidelines

As shown in Table 17, the MV-Bluefin vessel's systems are compared with the requirements for winterisation as dictated by the polar code method. After performing the induction survey for the MV-Bluefin research vessel, expert judgement will be provided in order to determine whether the systems aboard the MV-Bluefin can operate safely and effectively in polar regions.

Table 17: The winterisation methods for MV-Bluefin systems.

Structures/Systems	Items	Aboard the MV Bluefin Y/N	Potential Winterisation Methods
Hull Construction	Tanks	No	Heat tracing, air bubbler system, insulation, heating coils.
Equipment	Deckhouses	Yes	Heat tracing, insulation, ice repellent coatings, de-icing or anti-icing chemical application.
	Superstructures	Yes	Heating tracing, insulation, ice repellent coatings, de-icing or anti-icing chemical application.
	Anchoring arrangements	Yes	Heating tracing, insulation.
Vessel System and Machinery	Prime mover		Heat tracing, self-draining piping.
	Combustion air systems	Yes	Heat tracing, insulation.
	Anchor windlass	Yes	Heat tracing, ice repellent coatings.
	Cargo handling equipment	Yes	Heat tracing, ice repellent coatings, insulation.
	Piping systems	Yes	Heat tracing, insulation, self-draining piping.
	Electric systems	Yes	Heat tracing, insulation.

Structures/Systems	Items	Aboard the MV Bluefin Y/N	Potential Winterisation Methods
	Fire safety systems	Yes	Heat tracing, insulation, de-icing or anti-icing chemical application, chemical seals.
Safety Systems	Navigational equipment	Yes	Heat tracing, insulation.
	Launching stations and arrangements	Yes	Heat tracing, insulation, de-icing or anti-icing chemical application.
	Lifeboats	No	Insulation, ice repellent coatings.
Pressure Relief System	Pressure relief valves	No	Heat tracing.
	Emergency vapor depressurising equipment	No	Heat tracing, insulation.
Process Equipment	Process vessels (Fishing room)	No	Heat tracing, insulation, chemical seals.
	Process heat exchangers	No	
	Process electric heaters	No	
	Compressors	Yes	
	Pumps	Yes	
	Atmospheric storage tanks	No	
Process Pipe System	Thermal relief valves	Yes	Heat tracing, chemical seals.
	Block valves	Yes	
Safety System	Fire and gas detection Emergency shutdown station	Yes	Heat tracing, insulation, de-icing anti-icing chemical application, chemical seals.
Machinery Spaces	steering gear room (**Yes**), emergency fire pump room, CO2 rooms (**Yes)**, foam rooms (No), battery rooms, and bow thruster rooms (Yes**)**.	Yes/No	Heat tracing.
Lighting	Deck lights that do not generate sufficient heating to stay ice-free shall be fitted with additional heating to make them operational	No	Heat tracing.
Cranes	Cranes that are required for essential safety functions (e.g., crane used for launching the rescue boat.	No	(Heating) or passive (shielding).
Fuel Oil System	Fuel oil heating system (No) shall be sufficiently dimensioned to enable transfer of fuel under the design environmental conditions (Yes**)**	Yes/No	heat tracing.
Hydraulic Power Systems	Hydraulic fluid shall either be of a type that maintains an acceptable viscosity, or the hydraulic system shall have heating/circulation arrangements to keep fluids at an appropriate temperature	Yes	Hydraulic power systems
Engine Rooms, and Dead Ship Restart (Yes**)**	Machinery may require air intake heating, cooling water heating and lube oil heating (No), depending on individual machinery specifications, to ensure it can re-start from a dead-ship condition after 30 minutes.	Yes/No	Heat tracing.

The air bubbler system consists of a power cable, air release units, an automation system, compressors, and a range of pipes. By introducing air pressure into the vessel's system, the air bubbler detects the pressure required and therefore measures the water level and reduces propeller resistance, reducing the fuel consumption rate from 5% to 10% and increases the speed. In addition, this system has been approved by classification societies.

Table 18 shows the heat tracing and insulation system, aiming to preserve or raise the temperature of the pipes, and ultimately the vessel as a whole through the use of heat tracing cables. This occurs as a result of the electrical heating devices, which run along the length of the pipes in close physical proximity. This may be used in an effort to protect the pipes from freezing in the polar climate while also maintaining a constant flow temperature in hot water systems, as well as the preservation of temperatures in systems where various substances with different melting points are being transported. Table 19 represents justification for the assessment of winterisation systems aboard the MV-Bluefin.

Table 18: Potential issues arising on the MV-Bluefin as a result of polar temperatures.

System or Component	**Potential Problems**	**Y/N**
Lubrication oil	It is necessary to confirm all main propulsion and auxiliary prime movers are provided with lubricating oil maintained at the proper minimum temperature by the manufacturer's recommendations.	No
Bridge window	The ship will install electric heaters (No) and wipers (Yes) to clean some of the bridge windows for de-icing purposes; however, alternate bridge windows will not be provided with heaters and wipers.	Y/N
Anchor windlass	It is not clear how anchor-releasing arrangements are provided to reduce the effect of icing.	No
Bow door and stern ramps	The bow door and stern ramps are noted as hydraulically operated; it is not clear whether these systems are suitable for operations at the MAT (–25ºC); it is also uncertain that the seals used for the bow door will remain pliant at the low temperature (T_{MAT}).	No
Water pipelines	It is not clear how sanitary waterlines will be protected from freezing on decks and equipment; it is noted that the ships fire and wash water lines pass through decks and equipment and drawing in Appendix indicates that pipes are exposed to open air low temperature.	No
Valves	It is noted that the ramps and bow doors are hydraulically operated and the control valves are located on the surface deck, which is exposed to ambient temperatures; it is not clear how they will be protected from freezing in the harsh environment.	No
Air vent	It is not clear how the vents will be kept ice-free.	No
Emergency generator room	It is not clear whether the heating arrangements will be sufficient to heat the emergency generator room on deck 3 to 10ºC at the MAT.	No
Ventilators for HVAC system	It is not clear how the ventilators for the HVAC systems will be kept ice- and snow-free; they are protected from snow accumulation and icing problem that it may intervene with the effective operation of the closures and recirculation of exhaust gases.	No
Emergency power supply	The ABS (LTE) Guide/ DNV.GL have required that the auxiliary boiler and its controls be operable on the emergency source of power; it is not clear whether emergency heating will be provided to space where passengers will stay during a blackout; drawing number is indicated that any exposed pipes are to be insulated and heat traced even though drawing number does not indicate any heat tracing.	No
Engine room	The ABS (LTE), Guide/ DNV, have requirements that if any of the engines are to be on standby in low temperatures that the automation system includes a low-temperature alarm to notify the operator that the temperature is too low to start the machinery; not clear whether a low-temperature alarm will be included for the engine room.	No
Lifeboat engine	It is not clear whether the lifeboat engine will be able to perform its function at the design service temperature of -30ºC.	No
Lifeboat capacity	The ABS (LTE), Guide/ DNV, have required lifeboats be sized at 125% to accommodate bulky cold-weather clothing; it is noted that for example the POB is to be 210 and each lifeboat has a capacity of 120, which is approximately 114% sized.	No
Navigational equipment	Please confirm that the navigational equipment can operate in conditions the vessel is expected to operate at the design service temperature.	No
Escape route	It is not clear how escape routes will be kept from snow and ice and readily functional.	No
Exterior stairs	The exterior stairs are noted as being steeper than the 35ºC required by the LTE Guide and the stair material is not indicated as being grating as required by the LTE Guide.	Yes
Main switchboards	Switchboard for winterisation systems shall be arranged as required for distribution switchboards. A wattmeter or ampere meter, indicating the total load shall be installed on the switchboard. Marking on the switchboard shall state the load on each circuit, as well as the total load.	No

Table 19: Justifications for the assessment of winterisation systems aboard the MV-Bluefin.

Systems (Bluefin)	**Does it need winterization (DINW)**	**Justifications**
Bridge window	Yes	Ice/snow accretion often occurred on the bridge windows on the existing (MV-Bluefin); considering the same bridge window arrangement, winterisation is necessary; the new design for ship's (Bluefin) will have wipers and heaters for the de-icing purpose; heating requirements need to be identified; additionally, the new design does not have alternate heated windows, which is not in compliance with the LTE Guide; we need to consider the risk of reduced visibility when the unheated windows are blocked,
Escape route	No	Escape routes on the MV-Bluefin are not existing.
Exterior stairs	Yes	Ice/snow accretion often occurred on the exterior stairs of the existing Bluefin; the stair slopes of the old and new designs are the same; stairs on both designs are exposed to a harsh environment condition.
Lubricating oil	Yes	The questionnaire feedback showed that at approximately 20 ^{o}C the captain needed the lubricating oil to run the engine; risk exceeded the acceptable level.
Anchor windlass	Yes	Ice/snow accretion often occurred on the forecastle deck of the existing Bluefin, including anchor windlass/mooring equipment on deck; however, the thickness is less than 1 inch; this ice build-up on the anchor windlass could adversely affect the drop of the anchor in an emergency.
Bow door and stern ramps	No	Bow/stern ramps' hydraulic systems are not on the existing in the Bluefin. Based on the history, most ships never have had any operation problem as a result of low temperature; considering the same arrangements on the new bluefin design, hydraulic systems do not need to be winterised; however, there will be heaters in the ramps' hydraulic systems of the new design Bluefin; seals for bow doors will remain pliant assuming nitrile rubber is used; although the result showed that it may not be necessary to winterise the bow and stern ramps' hydraulic systems, they should always be well maintained for a cold environment, e.g., changing filters, check hoses and fittings
Water pipelines	Yes	Risk exceeded the acceptable level
Valves	No	It is noted that the control valves are located on deck, which is exposed to ambient temperatures; all hydraulic systems are inside; therefore, there should not be any icing problem; they will be functional regardless of hydraulic oil viscosity; the only noted hazard could be possible damage of valves caused by manual ice removal by mallets or hammers.
Air vent	Yes	The existing Bluefin does not have tank air pipes freeze or clog in low temperature either as a result of ice accretion or freezing of the ball to seal the vent pipe; if it is existing of the existing Bluefin is fully enclosed; the new Bluefin has air vent pipes exposed and this needs winterisation,
Emergency generator room	Yes	On the existing Bluefin has not existed the emergency generator compartment. As a result of cold temperature, a new design made to the new Bluefin should be considered for the winterisation requirements to be fulfilled.
Ventilators for HVAC system	No	On the existing Bluefin, the ventilation inlets have not been this system; the new design is safer than the old design with a higher intake position; it is facing inside, which makes it more preventive from spray; there is an option to circulate engine room air to provide heating to make it safer which is needed to maintain the engine room temperature at 10^{0}C; it is greater than the available propulsion machinery output (129hp/93.6 kw)
Engine room	Yes	The engine room needs to be heated to maintain its room temperature at 10^{o}C
Lifeboat engine	Yes	Captain of the existing Bluefin has experienced difficulties starting the lifeboat engine as a result of low temperature
Navigational equipment	Yes	No information regarding navigation equipment on the new design was provided; assumptions made for risk assessment; risk exceeded the acceptable level

HVAC, heating, ventilating, and air conditioning.

6.7 Conclusion

Based on expert consultation, it has been concluded that the systems onboard the MV-Bluefin vessel do not all align with the recommendations set out by the polar code, with particular cause-for-action associated with the temperature-sensitive sea chest systems, the auxiliary system required for heat tracing, the SWCS, as well as the SS. Thus, modification is required in order to mitigate potential system failure. However, this chapter investigates the MV-Bluefin's capacity to transport passengers, operate in polar regions, demonstrate the heat tracing and insulation system, preserve or increase the temperature of the pipes. This was in an effort to evaluate the various winterisation systems best onboard the vessel and ensure their compliance with the polar code. This will be achieved as part of the following objectives aforementioned. This research aims to collect old data of icebreaker and ice-capable research ships (greater than 500GT) from 2013 to 2019. These data were collected based on the literature review from different sources such as journal article, thesis, book, report and website and was validated. To select a suitable ice-class for the MV-Bluefin vessel operating in polar regions recommended by DNV, cold climate expertise has unique experience working in the polar regions with over 1,700 vessels with several ice-class notations represent above 30% of the DNV classed fleet. At present, DNV has in class up to 30 vessels with high ice class, including 19 ice breakers, which identified ice-class for Bluefin vessel can be operated in cold water regions. According to the DNV has developed several classifications that can be used to mitigate unwanted risks and several issues highlighted in this study. These classifications follow internationally recognised standard within the shipping community and ensure an individual ship is independently verified. DNV can issue statutory certificates for vessels operating in the Antarctic and may work on behalf of the flag administration.

Chapter 7: Developing the Numerical Risk Analysis Model in the Case of the MV-Bluefin Research Vessel

7.1 Introduction

Onboard the MV-Bluefin, the Australian Maritime College's flagship training and research vessel, are four major systems—the Seawater Cooling System (SWCS), the LOS, the FOS, and the accommodation and bridge insulation of heat tracing (ASI)—all of which are sensitive to the harsh environmental conditions of the Antarctic region.

This chapter aims to evaluate the power requirement of the MV-Bluefin in order to safeguard against system failure in the face of hostile polar temperatures, as well as identifying potentially vulnerable systems. Thus, Chapter 7 developed an innovate numerical model in order to classify the effects of harsh temperatures on various systems.

The above objectives can be achieved through:

- The identification of all major systems aboard the MV-Bluefin research vessel;
- The development of a numerical model based on seawater and air temperature respectively, which aims to estimate the energy required for the systems aboard the MV-Bluefin to maintain an internal temperature of 18°C despite outside temperatures; and
- An estimate of the power demand (W) for each system aboard the MV-Bluefin in order to identify trends and mitigate future risks.

7.2 Seawater Cooling System

The SWCS is one such system that may be adversely affected by the winterisation of the vessel in the inhospitable polar climate. This is due to the movement of SW throughout the vessel powered by a CP, which aims to draw heat away from the engines of the vessel by circulating SW through the sea chest, towards the heat exchanger, and finally to the engine itself [133, 134]. Table 20 represents the system properties of the MV-Bluefin. In order to determine the mass flow rate *m'* (kg/s) and the power required (W), the following equations [135] aim to calculate the system's demand (W) for each system which highlighted in Table 21 to 26.

$$Q = UA\Delta T_{lm} \qquad \text{………………. (1)}$$

$$\Delta T_{lm} = \frac{(\Delta T_2 - \Delta T_1)}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \qquad \text{………………. (2)}$$

$\Delta T_2 = T_{out,sw} - T_{in,oil}$ $\Delta T_1 = T_{in,sw} - T_{out,oil}$

$$Q = m' \left(\frac{kg}{s}\right) * Cp_{oil\left(\frac{J}{kg}.k\right)} * \Delta T_{lm} \text{ °C} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Table 20: System properties of the MV-Bluefin research vessel.

FOS		**LOS**		**SWCS**	
U	170 w/m^2.k	U	850 w/m^2.k	U	600 w/m^2.k
A	8 m^2	A	12 m^2	A	10 m^2
Q	99066 J/s	Q	112812 J/s	Q	100962 J/s
Cp, SW	4 J/g^{o}C	Cp, SW	4 J/g^{o}C	Cp, SW	4 J/g^{o}C
Cp, Light oil	2.09 J/g^{o}C	Cp, Light oil	2.38 J/g^{o}C	Cp, Light oil	2.13 J/g^{o}C

Table 21: Inputs for the above calculation for motor power demand.

SW Temperature at Intake, t_1 (ºC)	**Motor Power, *Pm* (W)**
-2	24.93
0	24.93
4	25.91
6	26.44
8	26.99
10	27.58
12	28.20

Table 22: Inputs for the above calculation for the mass flow rate of coolant.

SW Temperature at Intake, t_1 (ºC)	**Mass Flow Rate of Coolant, *m'* (kg/s)**
-2	24.48
0	24.93
4	25.91
6	26.44
8	26.99
10	27.58
12	28.20

Figure 50 shows the relationship between the SWCS power demand where the SW temperature ranges (ΔT) from -2 °C to 12 °C, thus demonstrating that the demand for pumping power falls in relation to the dropping temperature of the cooling fluid [136]. For the fluid to maintain in a liquid state at a temperature of 12°C, 28.25W are required. Thus, it is recommended that the fluid not fall below a temperature of -2 °C; the power is assumed constant below that point with a power demand of 25W in order to avoid freezing and subsequent systems failure. Further work may exist in determining the energy required for the heating of SW inputs below the temperature of -2°C.

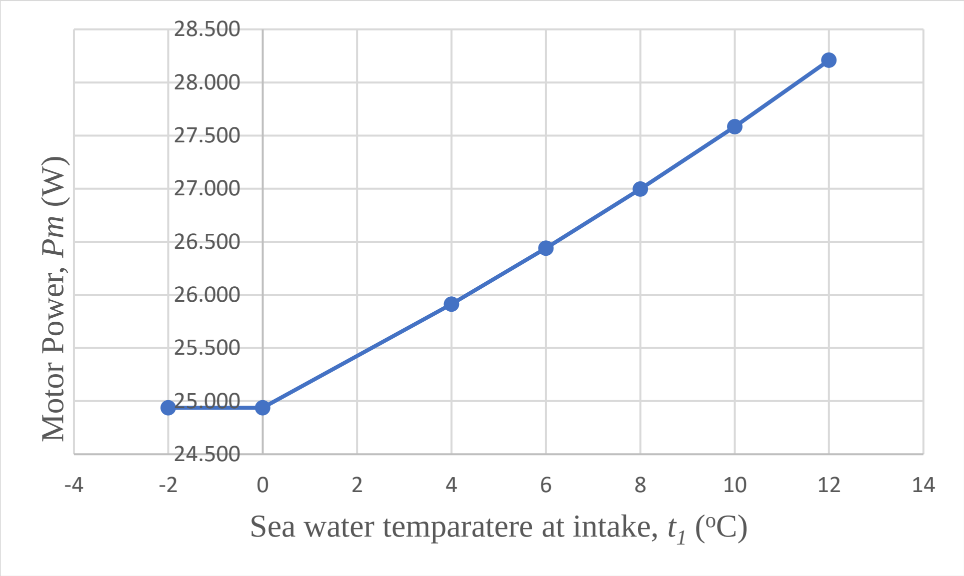

Figure 50: Relationship between the power demand (W) and the SW temperature of intake (ΔT) °C.

Figure 51 shows the relationship between the coolant's mass flow rate (kg/s) and the temperature difference (ΔT) ranging from -2 °C to 12 °C. As the coolant's mass flow rate is reduced, so too does the coolant temperature from 0.569 (kg/s) at 12°C to around 0.50 (kg/s) at 0 °C; the power is assumed constant below that point. In an effort to maintain the liquid state of the coolant, the mass flow rate cannot be reduced further than 0.50 (kg/s) at -2°C, as this may result in unintended systems failure [137].

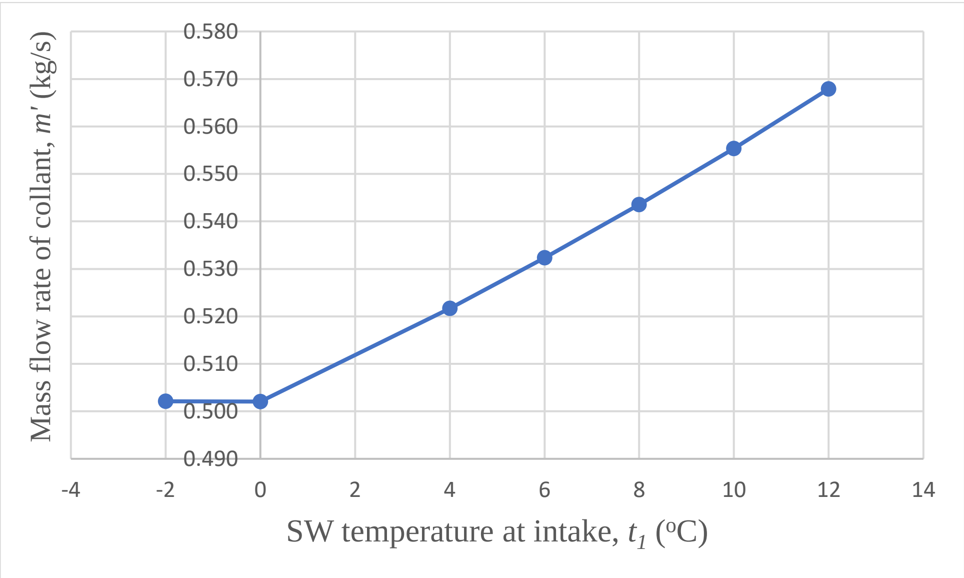

Figure 51: Relationship between the mass flow rate (W) and the SW temperature of intake (ΔT) °C.

7.3 Lubrication Oil System

The lubrication oil system (LOS), found inside the vessel's engine room, acts as a large loop whereby oil is suctioned from lower tanks to higher tanks by the pump. Much like the SWCS, this must remain in a fluid state, and therefore, a heat exchanger is essential to mitigate potential systems failure[138]. Table 23 provides inputs for the calculation of the LOS.

Table 23: Calculation inputs for the power demand of the LOS.

SW temperature at intake, t_1 (°C)	**Motor Power, *Pm* (W)**
-2	50.03
0	50.03
4	51.99
6	53.04
8	54.16
10	55.34
12	56.59

Figure 52 shows the relationship between the SW temperature at intake and the power requirement (W) of the LOS, with temperature difference (ΔT) ranging from -2°C to 12°C. As the temperature of the SW decreases, so too does the power demand. It is, however, assumed that once the temperature falls below -2 °C, the power is assumed to be constant below that point that the demand remains constant at 50W in an effort to ensure that a systems failure does not occur. As the temperature increases above 12°C, the power demand of the motor increases to 56.70W, although further research is required into the optimum temperature of the SW at intake, such that the system does not require excess power nor does the SW freeze.

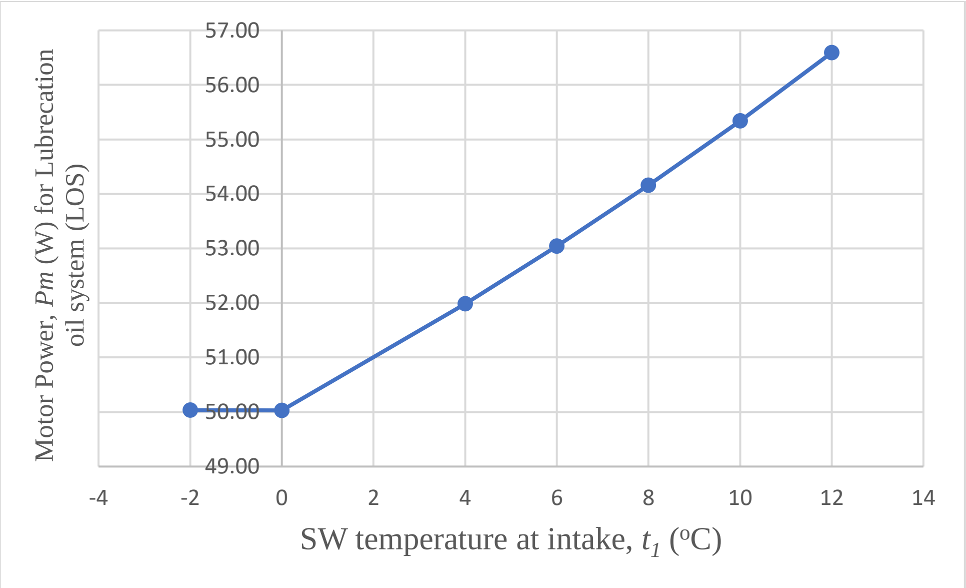

Figure 52: Relationship between the SW temperature at intake (°C) and the power demand of the motor (W).

7.4 Fuel Oil System

The transport of fuel throughout the vessel occurs such that oil housed in different tank locations may be transferred by a suction pump. An issue unique to the low temperatures of the polar regions, however, is that the viscosity of the fuel oil decreases in line with the ambient temperature and thus requires heating. Table 24 provides inputs for the calculation of the FOS [139].

Table 24: Inputs for the calculation of power requirements of the FOS.

SW Temperature at Intake, t_1 (ºC)	Motor Power, *Pm* (W)
-2	25.82
0	25.82
4	26.83
6	27.37
8	27.95
10	28.56
12	29.20

Figure 53 shows the relationship between the power demand (W) of the fuel oil heating system with the SW temperature at intake (°C), with a temperature difference (ΔT) ranging from -2 °C to 12 °C. As the temperature decreases, so too does the demand for power by the heating system with the power demand stagnating at -2°C; the power is assumed constant below that point with 25.75W. As the temperatures in the region fluctuate, an increased power demand exists at 12°C and 29.25W. While further work is required into the optimum temperature of SW at intake, it is not recommended that the vessel takes on SW below -2°C as this may lead to extremely high fuel oil viscosity and the subsequent freezing of the system.

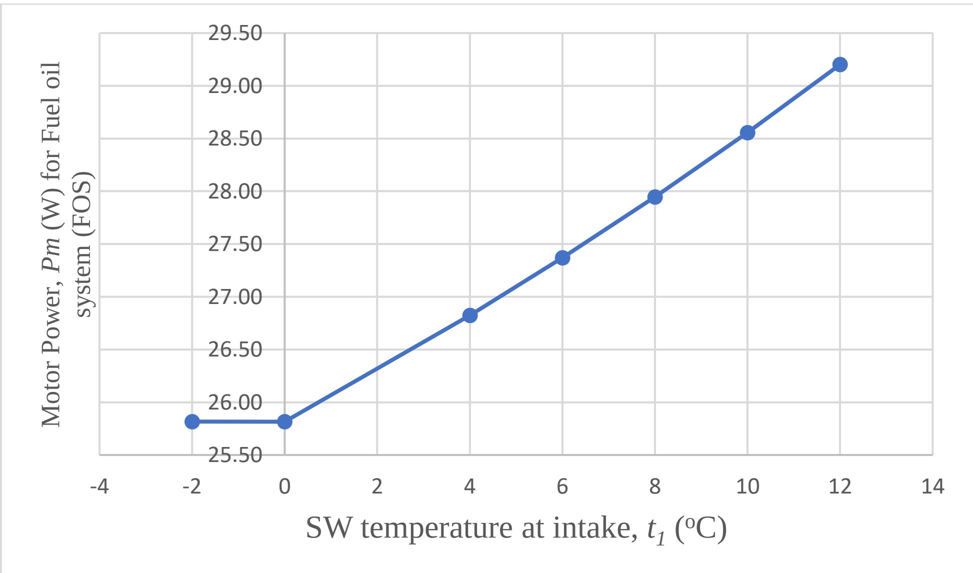

Figure 53: Relationship between SW temperature at intake (°C) and power demand (W).

7.5 Accommodation Insulation and Heat Tracing

The extreme temperature fluctuations, coupled with the harshness of the Antarctic region, ensures that most, if not all, of the equipment stored on the deck of the vessel are exposed to hazardous conditions which may affect function. Equipment, and crew members, housed inside the vessel suffer a similar fate in that low air temperatures affect their daily lives and duties. Thus, heat tracing is required in order to ensure that adequate heating is provided to areas such as the crew accommodation, the cabins, windows, hatch doors, and the navigation equipment [140]. Table 25 provides inputs for the calculation of the heating of the vessel.

Table 25: Inputs for the power demand calculation of the heating of the vessel.

Air Temperature at Intake, t_1 (°C)	Motor Power Demand, *Pm* (W)
-27	281.23
-22	272.16
-18	264.77
-15	259.14
-10	249.58
-5	239.79
0	229.72

Figure 54 shows the relationship between the ambient air temperature at intake (°C) and the power demand (W) for the vessel's heating systems, with temperatures (ΔT) ranging from 0 °C to -27°C as the air temperature plummets, so to make the demand for power.

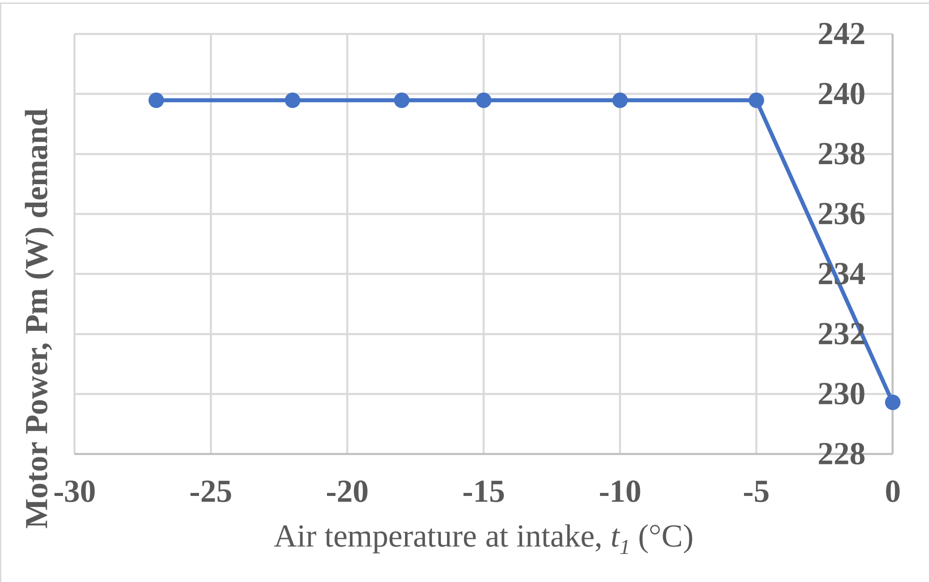

Figure 54: The relationship between the air temperature at intake (°C) and the power demand (W) for the heating of the vessel.

It can be seen from Figure 54 when the demand for power at 0°C, that equates to 230W, while at -27°C, 240W is required by the system. This means the AIS demands power increase when the ambient temperature decreases; the power is assumed constant below that point. However, further work is required for the optimum power requirement for subzero conditions to avoid the all-too-real loss of human life.

7.6 The Development of a Numerical Model in Maintaining an Ambient Internal Temperature of 18°C

The power requirements in order to maintain an ambient internal temperature of 18°C may be determined according to the numerical model developed by this thesis, where two vectors—SW temperature and ambient air temperature—are taken into consideration. Table 26 represents the relationship between temperatures (°C) to estimate the heating energy requirement. The assumptions made by the model include the following:

Thermal efficiency index (haa) = 0.8

Thermal efficiency index (haw) = 0.7

Air-air area (Aaa) = 525 m^2

Air-water area (Aaw) = 620 m^2

Air-air interface (U) = 5 W/(m^2k)

Air-water interface (U) =15 W/(m^2k)

Table 26: Relationship between temperatures (°C) to estimate the heating energy requirement.

	Air temperature, t_{air} (°C)						
SW temperature, t_{sw} (°C)	0	-5	-10	-15	-18	-22	-27
10	13.02	48.72	59.22	69.72	76.02	84.42	94.92
8	26.04	61.74	72.24	82.74	89.04	97.44	107.94
6	39.06	74.76	85.26	95.76	102.06	110.46	120.96
4	52.08	87.78	98.28	108.78	115.08	123.48	133.98
0	78.12	113.82	124.32	134.82	141.12	149.52	160.02
-2	78.12	113.82	124.32	134.82	141.12	149.52	160.02

Figure 55 shows the relationship between the demand for heating energy (Q; kW) and the fluctuations in air temperatures (t_{air}; °C) ranging between 0°C to -27°C and SW temperatures ($t_{sw;}$ °C) ranging between -2°C to 10°C in an effort to estimate the heating required to maintain an internal ambient temperature of 18°C. It can be seen that the heating energy requirement, (Q; kW) reached a peak at 225 kW at two temperature vectors, SW and air respectively. Thus, this thesis has determined that the MV-Bluefin cannot operate reliably in polar regions due to insufficient power and associated risk to life.

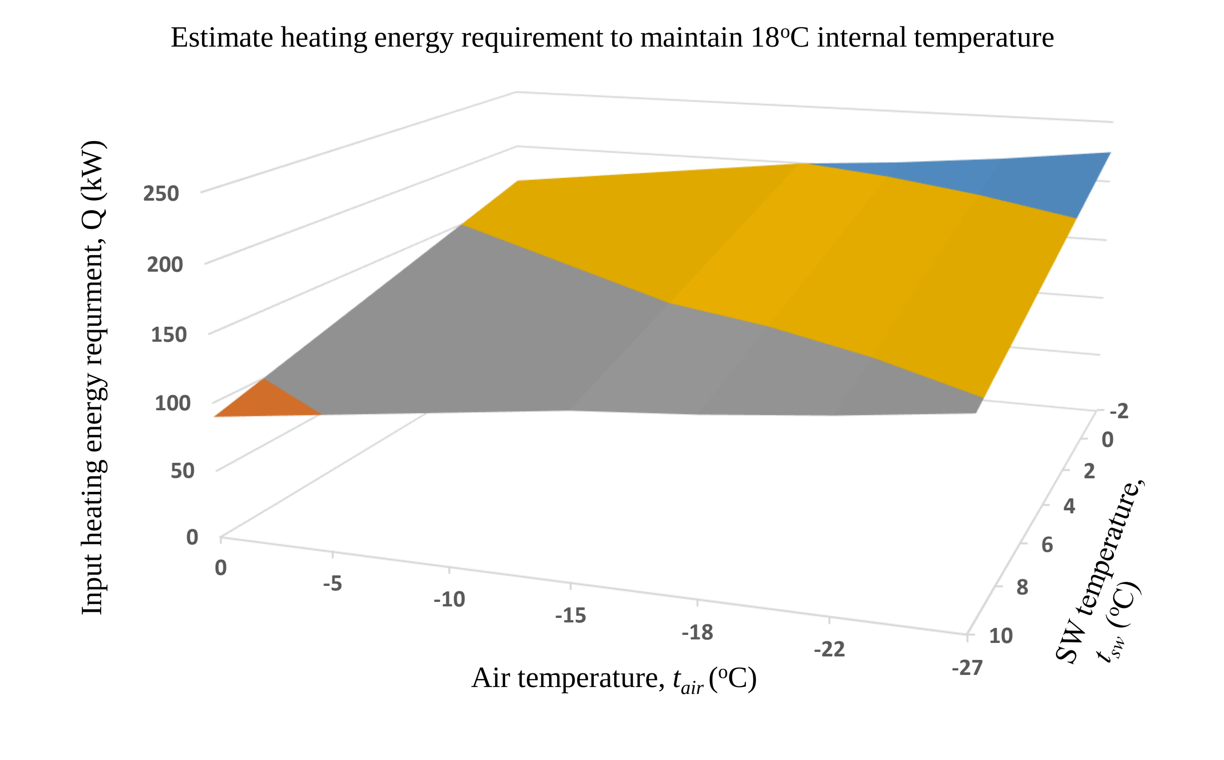

Figure 55: Relationship between the heating energy demand (Q; kW) and temperature difference (t_{sw} and t_{air}; °C).

7.7 Conclusion

In an effort to determine whether the MV-Bluefin was able to operate safely in polar regions, this thesis developed a numerical model to estimate the energy requirement for the vessel to maintain an internal ambient temperature that was suitable for both the success of the mission as well as the safeguarding of lives. As demonstrated in Figure 55, the MV-Bluefin is required to exert 225 kW to maintain a safe 18°C internal temperature, as well as requiring 25W to operate the SWCS safely, 50W to maintain the LOS, 25.75W to ensure adequate fuel viscosity in the FOS, and 240W to ensure adequate heating of the vessel. Thus, the MV-Bluefin is adversely affected by SW and air temperature and is ill-equipped to ensure safe passage throughout the polar region.

Chapter 8: Derivation of the Additional Risk Model and Risk Analysis for the Winterisation of the MV-Bluefin

8.1. Introduction

The operation of vessels in and around the Antarctic and Arctic regions has always been a matter of concern for the IMO as a result of harsh and inhospitable weather conditions, a distinct lack of infrastructure, remoteness and isolation from land, darkness and the distinct lack of accurate charts relative to other areas of the globe, as well as the harshness of the climate, the Antarctic region poses unique risks to shipping activity. Climate change, melting sea ice, and the enhanced possibilities for economic activity in the polar oceans have led to considerable attention in recent years and the implementation of new rules and regulations to protect human life and the marine environment. However, this system's winterisation for polar vessels must consider the new failure modes in this environment due to the presence of ice and reduction in seawater temperature affecting the standard temperature for the operating system. This may pose a big issue for the systems that cannot handle the dramatic temperature differences when entering from warmer to colder climates. As such, the identification of safety and risk power level indications, along with their performance, is crucial.

The chapter aims to develop an additional risk model and risk analysis for the winterisation of the MV-Bluefin’s systems when operating in the Antarctica region. The objective is to develop these additional models in order to calculate according to two-dimensional weather vectors (first coordinate sea-water temperature and second coordinate air temperature).
These objectives can be achieved by:

- The calculation of power demand as a function of ambient temperatures, through the use of randomised temperature measurements; and
- An estimation of power risk probability is identified when power demand exceeds the MV-Bluefin generators' power supply.

The power consumed by each system, including the SWCS, the fuel oil system FOS, the LOS, and the general heating of the vessel, is entirely reliant on the SW and air temperatures, respectively are shown in Table 27-30, and also seen in Appendix A1 – B1.

The MV-Bluefin research vessel relies on two main generators in the engine room, of which each produces 86 kW.

Total power produced = <172 kW

It is vital to note that the batteries room consumes an estimated 24 V, which relies on constant power. The power, however, is not reliant on the SW or air temperature. Table 27 represents the consumption of energy derived from the generator, and Table 28 represents the consumers which are using constant power (kW) below a set defined temperature according to the vessel's component.

Table 27: Consumption of energy derived from the generator.

Consumers of ship electricity	
Main fire pump	Hydrophone tank FW
Fire detection system	Boiler
Bow thruster pump	Bilge pump
Propulsion system	fuel purifier
Derrick	Oil separator
Ventilators for HVAC system	Navigational equipment
Emergency fire pump	Alarm system
Navigational equipment	Kitchen lights (CFL)
Batteries room	Living room lights (CFL)
Accommodation and utilities	Bedroom Lights
Mooring winch	Living room AC unit -1.5tons
Steering gear	Bedroom AC unit-1 tone
Baggage crane	Refrigerator
Crane	Electric water heater
Provision davit	Microwave Oven
Workshop equipment	Main Centrifugal pump
Incinerator	Ballast pump water
Welding equipment	Sea chest system
Starting air compressor	Coffee machine
Control air compressor	Electric clothes dryer
Plasma Tv	Desktop computer
Oil pump	Laptop
Seawater cooling pump	Windlass
Electric motor (Turbocharge)	Cargo pump converters

Table 28: Constant power used by the consumer.

Items	Power kW
Hydrophone tank FW	1.5
Electric water heater	4.0
Refrigerator	1.5
Main steering gear	3.4
Deck equipment (lifesaving appliances)	3.6
Bow thruster pump	8.0
Ventilators for HVAC system	1.5
Air vessel tank	0.05
Starting air compressor	2.86
Navigational equipment	1.9
Bilge pump	0.5
Alarm system	0.5
Electric motor (Turbocharge)	1.5
Total of power (kW)	**30.81**

Table 29: Power used by consumers that depends on the air temperature.

Components	Air temperatures (°C)						
	-27	**-22**	**-18**	**-15**	**-10**	**-5**	**0**
Provision davit, unit	2.33	2.14	1.98	1.90	1.84	1.75	1.50
Motor Gangway, unit	1.89	1.80	1.77	1.75	1.66	1.45	1.40
Electric motor wipers	1.01	1	0.99	0.90	0.86	0.80	0.78
Workshop equipment	2.3	2.01	1.9	1.87	1.33	1.11	0.99
Accommodation and utilities	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Mooring winch	7.90	7.55	7.02	6.5	6.33	5.99	5.52
Kitchen lights	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Living room lights	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bedroom Lights, unit	0.135	0.135	0.135	0.135	0.135	0.135	0.135
Microwave Oven, unit	1.3	1.29	1.25	1.02	1	0.99	0.92
Plasma Tv, unit	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Coffee machine	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Electric clothes dryer	3.9	3.89	3.82	3.79	3.71	3.69	3.65
Heat pump	1.99	1.82	1.53	1.44	1.40	1.35	1.30
Desktop computer &Laptop	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Total of power (kW)	**26.41**	**25.29**	**24.03**	**22.93**	**21.75**	**20.73**	**19.62**

Table 30: Power used by consumers that depends on the seawater temperature.

Components	Seawater temperature (°C)						
	-2	**0**	**4**	**6**	**8**	**10**	**12**
Emergency fire pump	7.33	6.53	6.02	5.88	5.30	4.66	4.11
Ballast pump water	4.96	4.21	3.45	3.11	3	2.64	2.22
Sea chest pump seawater	15.25	15.12	14.44	14.30	14.10	13.89	13.75
Cargo pump converters	11.05	10.95	10.89	10.82	10.77	10.70	10.55
Total of power (kW)	**38.59**	**36.80**	**34.80**	**34.11**	**33.17**	**31.89**	**30.63**

8.2 Power Demand-Supply Model

A vector of n seawater (SW) temperatures (°C) may be calculated as follows:

$$\vec{t}_{sw}^{\,fixed} = \left\{ t_{sw,1}^{fixed}, t_{sw,2}^{fixed}, \ldots, t_{sw,n}^{fixed} \right\}$$

where

$$T_{sw,\min} < t_{sw,1}^{fixed} < t_{sw,2}^{fixed} < \ldots < t_{sw,n}^{fixed} < T_{sw,\max}$$

Here, the maximum and minimum SW temperatures under consideration are denoted as $T_{\mathrm{sw,\,max}}$ and $T_{\mathrm{sw,\,min}}$. A vector of m air temperature (°C) may be calculated as follows:

$$\vec{t}_{air}^{\,fixed} = \left\{ t_{air,1}^{fixed}, t_{air,2}^{fixed}, \ldots, t_{air,m}^{fixed} \right\}$$

where

$$T_{air,\min} < t_{air,1}^{fixed} < t_{air,2}^{fixed} < \ldots < t_{air,n}^{fixed} < T_{air,\max}$$

Here, the maximum and minimum air temperatures under consideration are denoted as $T_{\mathrm{air,\,max}}$ and $T_{\mathrm{air,\,min}}$. The weather, in this case, is determined by a combination of SW temperature and air temperature. Let $\vec{W}$ be a random two-dimensional weather vector. Its first coordinate is the random variable "seawater temperature" T_{sw}, measured in °C. Its second coordinate is the random variable "air temperature" T_{air}, measured in °C:

$$\vec{W} = \{T_{sw}, T_{air}\}$$

The domain of possible values for the random weather vector $\vec{W}$ is:

$$\text{Domain}_W: \begin{cases} T_{sw} \in \left[T_{sw,\min}, T_{sw,\max}\right] \\ T_{air} \in \left[T_{air,\min}, T_{air,\max}\right] \end{cases}$$

Define $n \times m$ different fixed weather vectors as follows:

$$\vec{w}_{i,j}^{fixed} = \left\{t_{sw,i}^{fixed}, t_{air,j}^{fixed}\right\},\ i=1,2,\ldots,n;\ j=1,2,\ldots,m$$

For each $\vec{w}_{i,j}^{fixed}$, power demand (kW) may be calculated as:

$$D_{i,j}^{fixed}$$

Let the maximum power supply for the winterized "MV Bluefin" vessel be S kW.

Divide the two-dimensional weather space into $n \times m$ rectangles using the midpoints of $\vec{t}_{sw}^{fixed}$ and $\vec{t}_{air}^{fixed}$. These midpoints require calculation.

Define a vector of n+1 seawater margin temperature as follows:

$$\vec{t}_{sw}^{margin} = \left\{t_{sw,1}^{margin}, t_{sw,2}^{margin}, \ldots, t_{sw,n+1}^{margin}\right\}$$

where,

$$t_{sw,i}^{margin} = \begin{cases} T_{sw,\min} & \text{for } i = 1 \\ \left(t_{sw,i-1}^{fixed} + t_{sw,i}^{fixed}\right)/2 & \text{for } i = 2,\ldots,n \\ T_{sw,\max} & \text{for } i = n+1 \end{cases}$$

A vector of m+1 air margin temperature may be defined as follows:

$$\vec{t}_{air}^{margin} = \left\{t_{air,1}^{margin}, t_{air,2}^{margin}, \ldots, t_{air,m+1}^{margin}\right\}$$

where

$$t_{air,j}^{margin} = \begin{cases} T_{air,\min} & \text{for } j = 1 \\ \left(t_{air,j-1}^{fixed} + t_{air,j}^{fixed}\right)/2 & \text{for } j = 2,\ldots,m \\ T_{air,\max} & \text{for } j = m+1 \end{cases}$$

Now, the two-dimensional weather space can be divided into n x m rectangles $R_{i,j}$ as follows:

$$R_{i,j} = \left\{\vec{w}\left(t_{sw}, t_{air}\right) \mid t_{sw} \in \left[t_{sw,i}^{margin}; t_{sw,i+1}^{margin}\right] \text{ and } t_{air} \in \left[t_{air,i}^{margin}; t_{air,i+1}^{margin}\right]\right\}$$

for i=1, 2,…, n; j=1, 2,…, m

The main assumption is that the power demand in any two-dimensional point of the rectangle $R_{i,j}$ is constant and equal to $D_{i,j}^{fixed}$ kW. That is natural since the "centroid" of the rectangle $R_{i,j}$ is the fixed vector $\vec{w}_{i,j}^{fixed}$. In the three Power Risk Models which follow, we will assume that we have calculated and know:

- the rectangles $R_{i,j}$ for i=1,2,…,n; j=1,2,…,m
- the power demands $D_{i,j}^{fixed}$ for i=1,2,…,n; j=1,2,…,m
- the power supply S

The power grid is calculated using the MATLAB function `Power_demand_supply.m`, which is included in Appendix A. The source of data has been used from sections 7.2-7.5 for this function. The power demand $D_{i,j}^{fixed}$ is calculated for each of the rectangles $R_{i,j}$, where n=m=7. The output of the function is shown in Appendix A. The centroids of the rectangles, the power demand and the power supply for each rectangle are shown in Table A1 of Appendix A. The data for Table A1 is taken from the output parameters `SeawaterT_m`, `AirT_m`, `PowerDemand_total_m`, `PowerSupply`, `Code_m` of `Power_demand_supply.m`.

8.3 First Power Risk Model

It may be assumed that during a mission, the uncertainty about the worst possible weather combination is described with a two-dimensional cumulative distribution function (CDF) as follows [141]:

$$\mathrm{CDF}(\vec{w}) = \mathrm{CDF}(t_{sw}, t_{air}) = \Pr\{(T_{sw} \le t_{sw}) \cap (T_{air} \le t_{air})\}$$

Here $\vec{w} = (t_{sw}, t_{air})$ is an arbitrary point in the two-dimensional weather space.

The CDF at the point $\vec{w} = (t_{sw}, t_{air})$ is the probability that the seawater temperature will be less or equal to t_{sw}, and at the same time, the air temperature will be less or equal to t_{air}.

The domain of CDF is universal:

$$\mathrm{Domain}_{CDF}: \begin{cases} t_{sw} \in (-\infty; +\infty) \\ t_{air} \in (-\infty; +\infty) \end{cases}$$

The range of CDF is between 0 and 1 as any probability. The following properties hold:

$$\lim_{t_{sw} \to -\infty} \mathrm{CDF}(t_{sw}, t_{air}) = 0$$

$$\lim_{t_{air} \to -\infty} \mathrm{CDF}(t_{sw}, t_{air}) = 0$$

$$\lim_{t_{sw} \to +\infty} \lim_{t_{air} \to +\infty} \mathrm{CDF}(t_{sw}, t_{air}) = 1$$

The CDF is an increasing function of each of its arguments. The two-dimensional probability density function (PDF) is the second mixed-partial derivative of the CDF:

$$\mathrm{PDF}(\vec{w})=\mathrm{PDF}(t_{sw},t_{air})=\frac{\partial^2 \mathrm{CDF}(t_{sw},t_{air})}{\partial t_{sw}\partial t_{air}}$$

The domain of PDF is also universal:

$$\mathrm{Domain}_{PDF}:\begin{cases} t_{sw}\in(-\infty;+\infty)\\ t_{air}\in(-\infty;+\infty)\end{cases}$$

Define an area A in the two-dimensional weather space. The definite integral of the PDF over A is the probability that the random weather vector will belong to A:

$$\Pr\{\vec{W}\in A\}=\iint_A PDF(t_{sw},t_{air})\,\mathrm{d}t_{sw}\mathrm{d}t_{air}$$

The first approximation assumes that the worst possible weather combination can be described with a truncated two-dimensional normal distribution. The PDF of this distribution has the following form [142]:

$$PDF(\vec{w})=PDF(t_{sw},t_{air})=f(t_{sw},t_{air})$$
$$=\begin{cases}\dfrac{U}{2\pi|\mathbf{K}|}\exp\left\{-\dfrac{1}{2}(\vec{w}-\vec{m})^T\,\mathbf{K}^{-1}(\vec{w}-\vec{m})\right\} & \text{, for } \vec{w}\in\mathrm{Domain}_W\\ 0 & \text{, for } \vec{w}\notin\mathrm{Domain}_W\end{cases}$$

In the above formula:

$\vec{w}$ is a column weather vector $\vec{w}=\begin{pmatrix}t_{sw}\\ t_{air}\end{pmatrix}$;

$\vec{m}$ is the column vector of mean values $\vec{m}=\begin{pmatrix}m_{sw}\\ m_{air}\end{pmatrix}$

K is the 2 x 2 covariance matrix:

$$\mathbf{K}=\begin{pmatrix}\sigma_{sw}^2 & r_{sw,air}\sigma_{sw}\sigma_{air}\\ r_{sw,air}\sigma_{sw}\sigma_{air} & \sigma_{air}^2\end{pmatrix};$$

|K| is the determinant of K, equal to

$$|\mathbf{K}|=\sigma_{sw}^2\sigma_{air}^2-(r_{sw,air}\sigma_{sw}\sigma_{air})^2$$

K^{-1} is the inverse matrix of K

The scaling constant U has the reciprocal value of

$$1/U = \frac{1}{2\pi|\mathbf{K}|} \int_{T_{sw,\min}}^{T_{sw,\max}} \int_{T_{air,\min}}^{T_{air,\max}} \exp\left\{-\frac{1}{2}\left(\vec{w}-\vec{m}\right)^T \mathbf{K}^{-1}\left(\vec{w}-\vec{m}\right)\right\} \mathrm{d}t_{sw}\mathrm{d}t_{air}$$

Here, m_{sw} and σ_{sw} are the mean and the standard deviation of the random variable "seawater temperature", and m_{air} and σ_{air} are the mean and the standard deviation of the random variable "air temperature". The $r_{sw,air}$ is the Pearson Correlation Coefficient between the two random variables ("seawater temperature" and "air temperature"). The mean values are real numbers, whereas the standard deviations are positive real numbers, and a correlation coefficient is a real number between -1 and +1. The introduced real constant $U \geq 1$ ensures that the volume under the density surface over the area Domain_W is one; that volume represents the probability of the weather vector to be in the area Domain_W.

Under this assumption, we need to find the probability $P_{i,j}$ for the weather vector $\vec{W}$ to belong to the rectangle $R_{i,j}$. We can calculate $P_{i,j}$ using:

$$P_{i,j} = \mathrm{CDF}\left(t_{sw,i+1}^{margin}, t_{sw,j+1}^{margin}\right) - \mathrm{CDF}\left(t_{sw,i}^{margin}, t_{sw,j+1}^{margin}\right) - \mathrm{CDF}\left(t_{sw,i+1}^{margin}, t_{sw,j}^{margin}\right) + \mathrm{CDF}\left(t_{sw,i}^{margin}, t_{sw,j}^{margin}\right),$$

for $i=1,2,\ldots,n$; $j=1,2,\ldots,m$

The Power Risk for the ship of having bad weather condition is to fall in such a rectangle, where the demand is more than the supply, which means the failure of the power system of the ship.

$$Risk_{model\,1} = \sum_{\substack{i=1 \\ D_{i,j}^{fixed} > S}}^{n} \sum_{j=1}^{m} P_{i,j}$$

The first model may be formulated given:

- m_{sw}, m_{air}, σ_{sw}, σ_{air}, and $r_{sw,air}$
- The power demand-supply data

Find: The Power Risk, $Risk_{model1}$

The analytical calculation to find $Risk_{model1}$ can be performed using the following algorithm:

Step 1: Calculate the scaling constant U.

Step 2: Transform the truncated PDF into truncated CDF.

Step 3: Find probabilities $P_{i,j}$ for the weather vector $\vec{W}$ to belong to the rectangle $R_{i,j}$

for i=1, 2,…, n; j=1, 2,…, m.

Step 4: Calculate the Power Risk of the model $\boldsymbol{Risk_{model1}}$.

The $Risk_{model1}$ is calculated using the MATLAB function `Risk_norm_dist.m`. The source code and the function is included in Appendix B. It takes the power demand-supply data as input from `Power_demand_supply.m` as well as the parameters m_{sw}, m_{air}, σ_{sw}, σ_{air}, and $r_{sw,air}$. The output of the function is the probability for the two-dimensional temperature vector, which falls within each rectangle and the $Risk_{model1}$. For illustrative purposes, we have used m_{sw} =7°C, m_{air}= -1°C, σ_{sw} =30°C, σ_{air} =30°C, and $r_{sw,air}$ =0.5. The power supply was set to 220 kW, and the $Risk_{model1}$ was 0.1388. The output of the software is shown under the function in Appendix B. The centroids of the rectangles and the probabilities for the two-dimensional temperature vector to fall within each rectangle are shown in Table B1 of Appendix B. As expected, the sum of those probabilities equals one.

8.4 Second Risk Analysis Model

This model is much more elaborate, and the mission is assumed to consist of Q segments. The q segment (for q=1,2,…,Q) is c_q days, where the uncertainty about the weather combination of daily minimum seawater (SW) and air temperatures is described with a two-dimensional CDF as follows [143]:

$$\mathrm{CDF}_q\left(\vec{w}\right)=\mathrm{CDF}_q\left(t_{sw},t_{air}\right)=\Pr\left\{\left(T_{sw}\le t_{sw}\right)\cap\left(T_{air}\le t_{air}\right)\right\}$$

The domain of CDFq is universal:

$$\mathrm{Domain}_{CDF\,q}:\begin{cases}t_{sw}\in\left(-\infty;+\infty\right)\\ t_{air}\in\left(-\infty;+\infty\right)\end{cases}$$

The two-dimensional PDFq is the second mixed-partial derivative of the CDFq:

$$\mathrm{PDF}_q\left(\vec{w}\right)=\mathrm{PDF}_q\left(t_{sw},t_{air}\right)=\frac{\partial^2\mathrm{CDF}_q\left(t_{sw},t_{air}\right)}{\partial t_{sw}\partial t_{air}}$$

The domain of PDF_q is also universal:

$$\text{Domain}_{PDF_q}: \begin{cases} t_{sw} \in (-\infty; +\infty) \\ t_{air} \in (-\infty; +\infty) \end{cases}$$

The Power Risk that the winterized MV-Bluefin vessel will have at least one day of its mission without enough power, which will fail its mission, can practically be calculated only with computer simulation [144, 145].

B pseudo-realities (where *B* is at least 10000) is generated in Figure 56, where each simulation shows a full mission of $c=c_1+c_2+\ldots+c_Q$ days. For each day of the mission, a weather vector from the relevant segment's known distribution is simulated. The mission in the pseudo-reality will be a success if all *c* weather vectors fall into the rectangles $R_{i,j}$ where the demand $D_{i,j}^{fixed}$ is not greater than the supply *S*. If the count of pseudo-realities with successful missions is *L*, then the Power Risk of the second power risk model is the number of unsuccessful missions *B-L*, divided to *B*.

$$Risk_{model2} = \frac{B-L}{B}$$

This definition uses the frequentist approach to probabilities [141]. We have assumed that the PDF of the daily seawater temperatures and the air temperatures is described with two-dimensional normal distribution [142]:

$$\begin{aligned} PDF_q(\vec{w}) &= PDF_q(t_{sw}, t_{air}) = f_q(t_{sw}, t_{air}) \\ &= \begin{cases} \dfrac{U_q}{2\pi|\mathbf{K_q}|} \exp\left\{-\dfrac{1}{2}\left(\vec{w}-\vec{m}_q\right)^T \mathbf{K}_\mathbf{q}^{-1}\left(\vec{w}-\vec{m}_q\right)\right\} & \text{, for } \vec{w} \in \text{Domain}_W \\ 0 & \text{, for } \vec{w} \notin \text{Domain}_W \end{cases} \end{aligned}$$

In the above formula:

- $\vec{m}_q$ is the column vector of mean values $\vec{m}_q = \begin{pmatrix} m_{q,sw} \\ m_{q,air} \end{pmatrix}$
- $\mathbf{K_q}$ is the 2 x 2 covariance matrix $\mathbf{K_q} = \begin{pmatrix} \sigma_{q,sw}^2 & r_{q,sw,air}\sigma_{q,sw}\sigma_{q,air} \\ r_{q,sw,air}\sigma_{q,sw}\sigma_{q,air} & \sigma_{q,air}^2 \end{pmatrix}$

➢ The scaling constant U_q (for q=1,2,…,Q) has reciprocal value of:

$$1/U_q = \frac{1}{2\pi\left|\mathbf{K}_q\right|}\int_{T_{sw,\min}}^{T_{sw,\max}}\int_{T_{air,\min}}^{T_{air,\max}}\exp\left\{-\frac{1}{2}\left(\vec{w}-\vec{m}_q\right)^T\mathbf{K}_q^{-1}\left(\vec{w}-\vec{m}_q\right)\right\}\mathrm{d}t_{sw}\mathrm{d}t_{air}$$

Here, $m_{q,sw}$ and $\sigma_{q,sw}$ are the mean and the standard deviation of the random variable "sea water temperature at the q segment", and the $m_{q,air}$ and $\sigma_{q,air}$ are the mean and the standard deviation of the random variable "air temperature at the q segment". The $r_{q,sw,air}$ is the Pearson correlation coefficient between the two random variables ("seawater temperature at the q segment" and "air temperature at the q segment"). The mean values are real numbers, whereas the standard deviations are positive real numbers, and a correlation coefficient is a real number between -1 and +1. The introduced constant $U_q \geq 1$ ensures that for segment q the volume under the density surface over the area of Domain$_W$ is one; that volume represents the probability of the weather vector in segment q to be in the area of Domain$_W$.

The second model may be formulated given:

➢ c_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q) and B

➢ The power demand-supply data

Find: The Mission Power Risk, Risk$_{model2}$

The Monte Carlo simulation to find $Risk_{model,2}$ can be performed using the following algorithm:

1. Calculate the scaling constants U$_q$ for q=1,2,…,Q
2. Initialize L=0 (count of pseudo-realities without failures)
3. Repeat for each pseudo-reality b (for b=1,2,…,B)
    3.1. Repeat for each segment q, for q=1,2,…,Q
        3.1.1. Repeat for each day k, for k=1,2,…,c_q
            3.1.1.1. Generate a random weather vector $\vec{w}$ from $PDF_q\left(\vec{w}\right)$
            3.1.1.2. Find the rectangle $R_{icurr,jcurr}$ that $\vec{w}$ belongs to
            3.1.1.3. If $D_{icurr,\,jcurr}^{fixed} > S$, then declare a failure and go to step 4.
        3.1.2. End of the cycle for day k

3.2. End of the cycle for the segment q

4. L=L+1 (count the pseudo-reality as a success)

5. End of the cycle for pseudo-reality b

6. Calculate the risk of the model $Risk_{model2}=(B-L)/B$

The only point which needs additional explanations is 3.1.1.1. In reality, this generation is realized using the rejection method via the following steps:

1. A random variate $\vec{w}^{cand} = \left(t_{sw}^{cand}, t_{air}^{cand}\right)$ is generated from the untruncated normal density

$$PDF_q^{non-tr}(\vec{w}) = \frac{1}{2\pi\left|\mathbf{K_q}\right|} \exp\left\{-\frac{1}{2}\left(\vec{w}-\vec{m}_q\right)^T \mathbf{K_q}^{-1}\left(\vec{w}-\vec{m}_q\right)\right\}$$

2. Reject the candidate vector if it does not belong to Domain$_W$:

$$\text{If } t_{sw}^{cand} \notin \left[T_{sw,\min}, T_{sw,\max}\right] \text{ or } t_{air}^{cand} \notin \left[T_{air,\min}, T_{air,\max}\right] \text{ then, go to step 1}$$

3. Set the generated weather vector:

$$\vec{w} = \vec{w}^{cand} = \left(t_{sw}^{cand}, t_{air}^{cand}\right)$$

The $Risk_{model2}$ is calculated using the MATLAB function `Risk_simulate_eval_dist.m`. The text of the function is given in Appendix C. It takes as input the power demand-supply data from `Power_demand_supply.m` as well as the parameters c_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q) and B. The output of the function is $Risk_{model2}$. For illustrative purposes, we calculated the power risk of a mission that has Q=4 segments. The four segments are c_1, c_2, c_3 and c_4. These four segments represent c_1=4 days, c_2=5 days, c_3=3 days and c_4=2 days, respectively. For the first segment, the parameters of the two-dimensional truncated distribution of the temperatures $PDF_1(\vec{w})$ are: $m_{1,sw}$=6^{0}C , $m_{1,air}$=-10^{0}C, $\sigma_{1,sw}$=3^{0}C, $\sigma_{1,air}$=5^{0}C, $r_{1,sw,air}$=0.5. For the second segment, the parameters of $PDF_2(\vec{w})$ are: $m_{2,sw}$=4^{0}C , $m_{2,air}$=-12^{0}C, $\sigma_{2,sw}$=4^{0}C, $\sigma_{2,air}$=6^{0}C, $r_{2,sw,air}$=0.6. For the third segment, the parameters of $PDF_3(\vec{w})$ are:

$m_{3,sw}$=3^{0}C , $m_{3,air}$=-8^{0}C, $\sigma_{3,sw}$ =4.5^{0}C, $\sigma_{3,air}$ =6^{0}C, $r_{3,sw,air}$ =0.4. For the fourth segment, the parameters of $PDF_4\left(\vec{w}\right)$ are: $m_{4,sw}$=6^{0}C , $m_{4,air}$=5^{0}C, $\sigma_{4,sw}$ =3^{0}C, $\sigma_{4,air}$ =4.5^{0}C, $r_{4,sw,air}$ =0.5. The hypothetical power supply was set to 220 kW. The performed calculations have shown B=10000 pseudo realities. However, the $Risk_{model2}$ was 0.3614. The output of the function is shown in Appendix C. A complete report from the first three pseudo realities, which is the function's output, is given in Appendix C after the function. There is a power failure in the first pseudo-reality on day 4 of segment 1, in the second pseudo-reality on day 4 of segment 2. However, there was no power failure in the third pseudo-reality.

8.5 Third Power Risk Model

This model is an analytical version of the second model for the particular case when the two-dimensional distribution for any segments is a truncated bi-normal distribution. This model uses the first power risk model Q times to solve the problem set up in the second power risk model.

The main idea is straightforward. For each day of the q-the segment of the mission, the risk can be calculated using the first model:

$$P_{i,j,q} = \mathrm{CDF}_q\left(t_{sw,i+1}^{margin}, t_{sw,j+1}^{margin}\right) - \mathrm{CDF}_q\left(t_{sw,i}^{margin}, t_{sw,j+1}^{margin}\right) - \mathrm{CDF}_q\left(t_{sw,i+1}^{margin}, t_{sw,j}^{margin}\right) + \mathrm{CDF}_q\left(t_{sw,i}^{margin}, t_{sw,j}^{margin}\right),$$

for i=1, 2,…,n; j=1, 2,…,m; q=1,2,…,Q

where

$$\mathrm{PDF}_q\left(\vec{w}\right) = \mathrm{PDF}_q\left(t_{sw}, t_{air}\right) = f_q\left(t_{sw}, t_{air}\right)$$
$$= \begin{cases} \dfrac{U_q}{2\pi\left|\mathbf{K_q}\right|} \exp\left\{-\dfrac{1}{2}\left(\vec{w}-\vec{m}_q\right)^T \mathbf{K}_{\mathbf{q}}^{-1}\left(\vec{w}-\vec{m}_q\right)\right\} & \text{, for } \vec{w} \in \mathrm{Domain}_W \\ 0 & \text{, for } \vec{w} \notin \mathrm{Domain}_W \end{cases}$$

and

$$\mathrm{PDF}_q\left(\vec{w}\right) = \mathrm{PDF}_q\left(t_{sw}, t_{air}\right) = \frac{\partial^2 \mathrm{CDF}_q\left(t_{sw}, t_{air}\right)}{\partial t_{sw} \partial t_{air}}$$

For more explanations on CDF_q and PDF_q, see the Second Power Risk Model.

Then the Power risk for each of the days form the q-the segment will be:

$$Risk_q = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ D_{i,j}^{fixed} > S}}^{m} P_{i,j,q}$$

The mission Power Risk can be calculated considering that a successful mission means the power supply to be not less than the power demand for each day of the mission:

$$Risk_{\text{model3}} = 1 - \prod_{q=1}^{Q} \left(1 - Risk_q\right)^{n_q}$$

The second model may be formulated given:

- n_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q)
- The power demand-supply data

Find: The Mission Power Risk, $Risk_{model3}$

1. Calculate the scaling constants U_q for q=1,2,…,Q
2. Repeat for each segment q, for q=1,2,…,Q

   2.1. Set m_{sw}=$m_{q,sw}$, m_{ai}=$m_{q,air}$,r, $\sigma_{sw} = \sigma_{q,sw}$, $\sigma_{air} = \sigma_{q,air}$, and $r_{sw,air} = r_{q,sw,air}$

   2.2. Use the First Power Risk model to calculate the daily risk in segment q:

$$Risk_q = Risk_{\text{model1}}$$

3. Calculate the Mission Power Risk of the model $Risk_{model3}$

The $Risk_{model3}$ is calculated using the MATLAB function `Risk_generalized_model.m`. The source code and the function are included in Appendix D. It takes the power demand-supply data as input from `Power_demand_supply.m` as well as the parameters c_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q). The output of the function is the $Risk_{model3}$ and the power risk for each of the segments. For illustrative purposes, the power risk of a mission with the same parameters as the one described at the end of section 8.4 is calculated. The output for $Risk_{model3}$ was 0.3703. The output of the function is shown in Appendix D. The power risk for each of the segments is given in Appendix D after the function. As evident, the Third Power Risk model results practically coincide with those from the Second Power Risk model. However, the function `Risk_simulate_eval_dist.m`. with 10000 pseudo realities calculated the results in 8.37 seconds, while the `Risk_generalized_model.m`. calculated the results in 0.074 seconds, which is more than 100 times faster.

8.6 Mission power risk against the hypothetical power supply

The $Risk_{model3}$ is calculated using the MATLAB function `Risk_generalized_model.m`. The source code and the function are included in Appendix D. It takes the power demand-supply data as input from `Power_demand_supply.m` as well as the parameters c_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q). The output of the function is the $Risk_{model3}$ and the power risk for each of the segments. For illustrative purposes, the power risk of a mission with the same parameters as the one described at the end of section 8.4 is calculated. The output of $Risk_{model3}$ was 0.3703. The output of the function is shown in Appendix D. The power risk for each of the segments is given in Appendix D after the function. As evident, the Third Power Risk model results practically coincide with those from the Second Power Risk model. However, the function `Risk_simulate_eval_dist.m`. with 10000 pseudo realities calculated the results in 8.37 seconds, while the `Risk_generalized_model.m`. calculated the results in 0.074 seconds, which is more than 100 times faster.

The mission power risks for several different values of the hypothetical power supply can be calculated using the Second and Third Power Models. In this way, the mission power risk as a function of the hypothetical power supply can be obtained, which is useful to determine the investment in a separate mission. This relation is evaluated with the MATLAB function `PowerSupply_Risk_curve.m`. The source code of the function is included in Appendix E. It takes as input the power demand-supply data from `Power_demand_supply.m` as well as the parameters c_q, $m_{q,sw}$, $m_{q,air}$, $\sigma_{q,sw}$, $\sigma_{q,air}$, $r_{q,sw,air}$ (for q=1,2,…,Q), and B. The important input parameter is the array *`PowerSupplyH_v`* which contains the values of the hypothetical power supplies for which the power risks will be calculated with the second and the third power models. The function generates graphical output, as shown in the sections of Figure 56. For illustrative purposes, the power risk curve of a mission with the same parameters (as the one described at the end of section 8.4 for hypothetical power supply for any whole kW from 160 till 270) is calculated. The output of the function is shown in Appendix E. The resulting functions are shown in Figure 56, obtained for different pseudo realities (50, 100, 1000 and 10000).

The simulation curves approach the analytical curve (a-b) with 50 and 100 pseudo-realities, although the difference between the two methods is easily visible. There is no practical difference between the curves under 1000 pseudo realities. At 10000 pseudo realities, the two curves coincide, so 1000 pseudo realities are sufficient to achieve precision. Such a power supply curve is useful for decision-makers to determine the suitable condition or additional power for the smooth operation of the vessel.

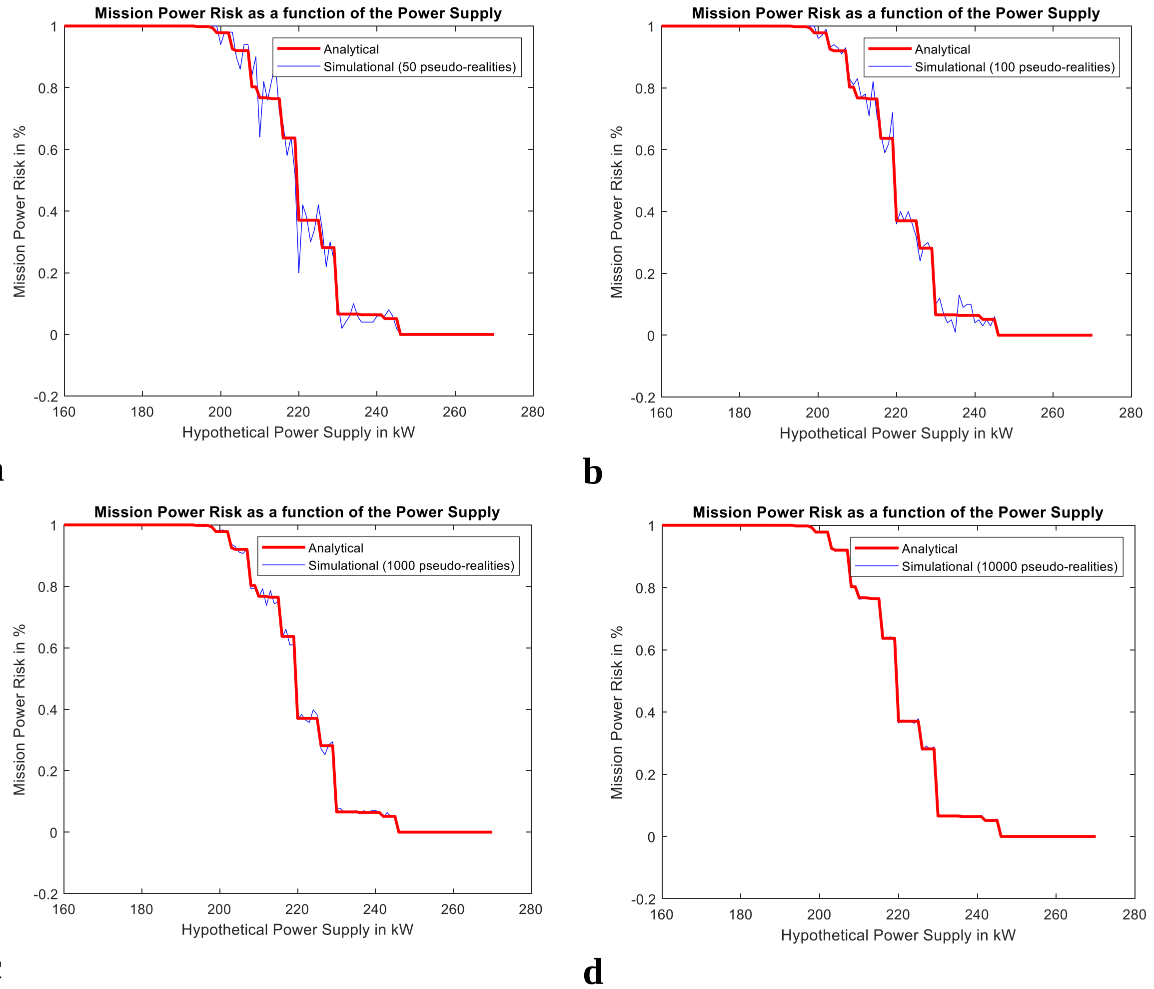

Figure 56: (a-d) Model risk between the Hypothetical Power Supply (kW) and Mission Power Risk (%): (a) with 50 pseudo realities; (b) with 100 pseudo realities; (c) with 1000 pseudo realities; (d) with 10000 pseudo realities

8.7 Conclusion

This chapter developed a new methodology in order to address the winterisation of four-ship systems in the harsh polar regions while working within the IMO guidelines established as part of the polar code. The two models whereby the power risk was assessed can be found in Appendix A. The first model distributed extreme weather vectors according to a truncated bi-normal distribution. The power risk is analytically derived as the integration of the truncated bi-normal PDF over the critical region, denoted as the weather vector region where power failure will occur. The second model divided the vessel’s route into an arbitrary number of segments, where each segment consists of several days with the daily weather vector distributed according to a segment truncated bi-normal distribution. The power risk is derived using a computer simulation of 10000 pseudo-missions. A pseudo-mission consists of daily weather vectors being randomly generated according to the known specific segment truncated bi-normal distributions. The mission is considered a success if all the weather vectors appear outside the critical region. For both models, the power risk is calculated as a function of ambient temperatures. The power grid is calculated using the MATLAB function `Power_demand_supply.m`. The power risk analysis function is included in Appendix A through E and was developed using MATLAB.

To estimate the probability of power risk, the models developed in this chapter take a wide range of factors into consideration, including vessel dynamics, operational and environmental factors, and human factors, and is, therefore, able to provide an early warning. As such, the proposed methodology may assist in real-time decision-making and allow for appropriate preventative measures to enhance the vessel's safety and operation.

Chapter 9: Discussion and Conclusions

This chapter presents the main conclusions of this research as well as a number of recommendations for further work.

9.1. Summary of Work

The methodological aim of this thesis is to develop different winterisation models for MV-Bluefin research vessel systems operating in harsh environmental conditions. Specific analysis can be found in the related chapter:

Chapter 2 reviewed the IAATO [3], an organisation founded by private-sector operators to practice and promote ecologically sustainable and environmentally responsible tourism in the Antarctic region. This review was done in light of the legislation set out by the ATS, the IMO and the POLAR VIEW (which is a chapter of the Polar code) [5-9], and the IACS [14].
This was achieved through:

- The identification of ATS legislation which currently regulates all activities conducted below 60°S;
- The review of POLAR VIEW, as well as IACS and IAATO; and
- The evaluation of the SAR exercise undertaken by IAATO with the MRCC based in Buenos Aires, Argentina. This was undertaken in an effort to mitigate the distinct lack of infrastructure in regions where the polar code is highly applicable.

Chapter 2 concluded that the regulation of tourist activities in the Antarctic region below 60°S occurs in a number of different ways and through a number of different bodies, including the IAATO, the Antarctic Treaty itself, the Protocol on Environmental Protection (Madrid Protocol), which forms part of the ATS, as well as the POLAR VIEW (which is a chapter of the Polar code). Furthermore, DNV aims to develop environmental sections supplemental to the polar code, which would ban the use of heavy fuel oil [5, 25]. The inter-governmental and inter-agency management of polar regions presents a unique challenge, and SAR exercises and related initiatives are essential in building relationships, trust and understanding.

Chapter 3 reviewed the literature, published statistical data and reported accidents in order to determine the number of accidents occurring, the type of accidents occurring, the vessel most likely to be involved in an accident, as well as any casualties resulting in such accidents. Thus,

Chapter 3 aimed to provide recommendations such that the polar code may be applied as safely as possible for vessels operating in the Antarctic region.
This was achieved through:

- A review of both the type of vessel involved, as well as the nature of the accident which occurred in Antarctic waters, including collapse, explosion, foundering, or sinking;
- The evaluation of the historical frequency of such accident events; and
- An identification of any vessels which may have been lost as a result of the accident.

The unique challenges presented by the polar regions requires highly specialised equipment, experienced and knowledgeable crew members, as well as expensive and comprehensive insurance. Despite taking all precautions, however, the harsh environment presents an almost insurmountable hazard resulting in a vast number of accidents, with 68.5% in global scale occurring as a result of human error or direct human action, and 20% occurring as a result of system or equipment failure. In the case of a vessel such as Australian icebreaker the RSV Nuyinya, human error may be compounded in that a wide range of activities occur on board as well as the vessel participating in a number of internal and external missions, thus increasing the risk of an accident occurring which was marked by the European Maritime Safety Agency with the recommendation that additional training is provided to staff members and crew in order to reduce human error.

Chapter 4 reviewed the operations, routes, and winterization of a variety of polar vessels in the Antarctic region as well as the frequency and duration of their missions in an effort to assist vessels in transiting through the harsh Southern Ocean.
This was achieved through:

- A review into the most common routes taken by vessels throughout the region, as well as differentiating between destinations across three summer seasons, with the most common destinations including the Antarctic Peninsula, the Ross Sea, South George, the Weddell Sea, and the Southern Ocean;
- The survey of vessel types travelling throughout the region between 2016 and 2019;
- The analysis of statistical data collected during the 2016 summer season regarding vessel accidents and casualties in the Southern Ocean;
- The identification of key stakeholders, and the subsequent mapping of relationships and dependencies in the Antarctic region; and

- The identification of accident trends within the Southern Ocean, specifically within the predefined areas 103 and 104 respectively based on the sea state divided.

Chapter 4 concluded that despite the hazardous conditions posed by the region, the Antarctic Peninsula was the most attractive tourist destination, with a yearly total of 322 trips made by a variety of vessels, while the Ross Sea is the most common destination for research vessels, resupply vessels and fishing vessels. Comparatively, South Georgia and the Weddle Sea were much less attractive to all sectors. The harsh physical conditions which would have been endured by the vessels have been documented in this chapter, and it has been found that the environmental conditions may not influence the characteristics of the subsurface formations in the Antarctic regions. The delicate elements involved in the operation of the vessel, however, could be adversely affected by both salinity and temperature. In the predefined areas 103 and 104, the salinity in the Antarctic region ranged between 33.8 ppt and 34.7 ppt, such that the Antarctic bottom water had a salinity of 34.7 ppt at a temperature of -0.4 ^{o}C, while the Antarctic circumpolar water had a salinity of 34.6-34.7 ppt at a temperature of 0-2.0 ^{o}C.

Chapter 5 critiqued the polar code, developed by DNV, which regulates the operation of vessels in polar regions. The two stages considered by this thesis are those which identify the critical components which are negatively affected by low-temperatures and icing conditions and the subsequent drafting and implementation of guidelines; as well as the application of safety functions and techniques for both machinery space and auxiliary machinery.
This was achieved through:

- A review into DNV's classification of vessels undergoing winterisation, which applies to all stages of the commission, design, construction, and operation;
- An evaluation of the guidelines establishes as part of the polar code, as well as all additional requirements regarding the structural integrity of the hull and machinery space;
- A review into the Statutory Navigation Requirements for Polar Vessels;
- A description, including technical details, of the SWCS and the SWCCS;
- The use of the Failure Mode and the Effect Analysis (FMEA) methodology in providing recommendations for the operation of the MV-Bluefin research vessel in polar climates;
- The analysis of the Seawater Central Cooling System Chest (SWCCSC) aboard the MV-Bluefin, and the identification of weak points; and

- An evaluation of the effects of winterisation on the SWCS.

Chapter 5 concluded that the safety of polar vessels relies on the guidelines laid out in the polar code, including construction, design, equipment, maintenance, and operations of the vessel, as well as the overarching environmental protections. Such guidelines and regulations have allowed for human activity and the use of ARVs in previously inaccessible, harsh, and hostile polar regions. While still undergoing development, the requirements outlined by all relevant and authoritative bodies have ensured that vessels operating in the polar regions are fit for their intended use, thereby reducing the rate of accidents or failures. This can be seen in that all machinery installations must prove to be functional under a wide range of anticipated environmental conditions, including ice and snow accretion or accumulation, ice and snow ingestion from seawater, the increased viscosity of liquids as a result of various freezing stages, and the temperature of seawater intake that can be recommended for this study.

It is recommended that sea bays and sea boxes adhere to the following design characteristics:

1. Reduce ice, snow, or slush ingestion with the implementation of a strainer plate at the inlet with perforations measuring 20 mm in diameter;
2. Submerged as deeply as possible;
3. Locate both sea bays and boxes on either side of the ship respectively;
4. The suctions from the sea bay should equal 20% of the total open area to the sea;
5. Clear sea inlets through the use of low-pressure steam or air system; and
6. Ensure that a vent with a cross-sectional area greater than or equal to the pipes is open to the atmosphere.

Ice blockages can be prevented further by implementing a vertical plate weir, which allows entering ice to float, thereby reducing the risk of ingestion through the strainer. This, however, does result in ice accumulation at the top of the tank, requiring means of clearing it.

Chapter 6 provided an overview of the MV-Bluefin’s capacity to transport passengers, operate in polar regions, demonstrate the heat tracing and insulation system, preserve or increase the pipes' temperature. This was to evaluate the various winterisation systems best onboard the vessel and ensure their compliance with the polar code.

This was achieved through:

- The evaluation of the critical equipment aboard the MV-Bluefin and their application to the polar code;

- A comparison of the vessel's specifications with the guidelines laid out in the polar code to determine whether the MV-Bluefin meets the requirements for winterisation;
- The identification and assessment of potential issues arising aboard the MV-Bluefin as a direct result of the hostile polar temperatures;
- The identification of the optimal SWCS for the winterisation requirements of the MV-Bluefin; and
- A review into the onboard systems and whether they align with the polar code and other related guidelines.

Chapter 6 concluded that the systems onboard the MV-Bluefin vessel do not all align with the recommendations set out by the polar code, with particular cause-for-action associated with the temperature-sensitive sea chest systems, the auxiliary system required for heat tracing, the SWCS, as well as the SS. Thus, modification is required in order to mitigate potential system failure.

Chapter 7 evaluated the power requirement of the MV-Bluefin to safeguard against system failure in the face of hostile polar temperatures and identify potentially vulnerable systems. Thus, Chapter 7 developed an innovative numerical model to classify the effects of harsh temperatures on various systems where the power is assumed constant below that point 0^{o}C. This was achieved through:

- The development of a numerical model based on seawater and air temperature respectively, which aims to estimate the energy required for the systems aboard the MV-Bluefin to maintain an internal temperature of 18°C despite outside temperatures; and
- An estimate of the power demand (W) for each system aboard the MV-Bluefin identifies trends and mitigates future risks (the power is assumed constant below that point -2^{o}C).

Chapter 7 concluded; those systems aboard the MV-Bluefin are adversely affected by the ambient temperature, in that the power demand decreases in line with the temperature of the cooling fluid. For the fluid to maintain in a liquid state at a temperature of 12°C, 28.25W are required. Thus, it is recommended that the fluid not fall below a temperature of -2°C with a power demand of 25W in order to avoid freezing and subsequent systems failure where the power is assumed constant below that point -2^{o}C.

Chapter 8 evaluated the additional risk of winterisation in the Antarctic regions in the form of a risk analysis, calculated on a two-dimensional weather vector grid where the first coordinate relates to SW temperature and the second coordinate relates to ambient air temperature. These are calculated as additional to the standard failure risk of the MV-Bluefin, the probability of power failure is denoted as power risk. This was modelled in MATLAB.

This was achieved through:

- The calculation of power demand as a function of ambient temperatures, through the use of randomised temperature measurements; and
- An estimation of power risk probability is identified when power demand exceeds the power supply from the MV-Bluefin generators.

Chapter 8 developed a new methodology to better address the winterisation of four-ship systems in the harsh polar regions while working within the IMO's Polar Code guidelines. The two models whereby the power risk was assessed can be found in Appendix A. The first model distributed extreme weather vectors according to a truncated bi-normal distribution. The power risk is analytically derived as the integration of the truncated bi-normal PDF over the critical region, denoted as the weather vector region where power failure will occur. The second model divided the vessel's route into an arbitrary number of segments, where each segment consists of several days with the daily weather vector distributed according to a segment truncated bi-normal distribution. The power risk is derived using a computer simulation of 10,000 pseudo-missions. A pseudo-mission consists of daily weather vectors being randomly generated according to the known specific segment truncated bi-normal distributions. The mission is considered a success if all the weather vectors fall outside the critical region. For both models, the power risk is calculated as a function of ambient temperatures. The risk analysis function is included in Appendix A through E and was developed using MATLAB.

Chapter 8 takes a wide range of factors into consideration, including vessel dynamics, operational and environmental factors, and human factors to estimate the probability of power risk to provide an early warning. As such, the proposed methodology may assist in real-time decision-making and allow for appropriate preventative measures to enhance the vessel's safety and operation.

9.2. Discussion and Findings

The Antarctic region, defined by Article VI of the AT as the area below 60°S, has been subject to increased ship traffic in recent years in the form of research, tourism, and bioprospecting. As such, scrutiny must be placed on both the legislation governing the region and activities occurring within it and the vessel and crew's ability and capacity to ensure safe passage through the notorious Southern Ocean. This thesis aims to understand how the aforementioned legislation applies to vessels operating in the region and the risks posed to vessels, their operating systems, and the lives on board while specifically referencing the MV-Bluefin, the Australian Maritime College’s 35m-long flagship training vessel.

The Southern Ocean presents unique challenges to mariners and vessels alike, with the harsh temperatures, icing conditions, and salinity often resulting in damage to the operating systems, the accidental collapse, explosion, foundering, or sinking of the vessel, and potentially causing the subsequent loss of human lives. In an effort to mitigate such risks, DNV outlined the polar code related to the construction, design, equipment, maintenance, and operations of the vessel and has resulted in fewer casualties in the Antarctic region. This thesis, however, has made a number of additional recommendations to reduce the rate of accidents further and has demonstrated that the polar code is insufficient in safeguarding against system failure in the face of hostile polar temperatures. The two models described in Chapter 8 aim to provide the crew with a means of early detection to assist in real-time decision-making and allow for appropriate preventative measures to enhance the vessel's safety and operation.

This thesis has also demonstrated that the MV-Bluefin does not adhere to the winterisation requirements set out by the polar code and has identified several complex systems, including the temperature-sensitive sea chest systems, the auxiliary system required for heat tracing, the SWCS, as well as the SS. Therefore, it is recommended that modification of the MV-Bluefin take place to mitigate potential system failure and subsequent accidents.

9.3. Future Work

Further research may be undertaken in a number of areas, including the following:

Uncertainty analysis: Uncertainty analysis can be integrated as part of the data analysis and recommendations.

Improved data collection: The study may be expanded with the use of more accurate and detailed data measurements, that are collected and stored for scientific research.

Operating condition: In future studies, we can concentrate on exploring other conditions of vessels in harsh environments.

Study of natural hazards: Future studies can explore the impact of various natural hazards in vessel operations in harsh environments.

Expert elicitation: The existing methodology may be expanded with the use of expert knowledge relevant to the problem at hand in order to further improve approaches and technique.

Other approaches: As a direction for future studies, we can compare the proposed methodology from this thesis with other statistical approaches and perhaps achieve improvements as a result of the comparisons.

9.4. Conclusion

The operation of vessels in and around the Antarctic and Arctic regions has always been a matter of concern for the IMO as a result of harsh and inhospitable weather conditions, a distinct lack of infrastructure, remoteness and isolation from land, darkness and the distinct lack of accurate charts relative to other areas of the globe, as well as the challenges presented by communication systems and other navigational aids. As such, the identification of safety and risk power level indications, along with their performance, is crucial.

This thesis has considered the MV-Bluefin’s winterization in the context of the vital seawater (SW) cooling system, which transfers waste heat away from the operating systems in an effort to better assist the vessel in withstanding the harsh climatic conditions. In the context of the MV-Bluefin, the power demand of the vessel is calculated for a grid of two-dimensional weather vectors—SW temperature as the first coordinate and air temperature as the second—where the power demand of the MV-Bluefin may exceed the available power supply from the generators as a direct result of the extreme temperature fluctuations. Identified as a power risk, the probability of the aforementioned failure is additional to the vessel's standard failure risk. This thesis has developed two models for assessing such power risk.

According to a truncated bi-normal distribution, the first model distributes the extreme weather vector, with the power risk analytically derived as an integration of this PDF over the critical region, which is identified as the weather vector area where the power failure is expected to occur. Conversely, the second model divides the vessel's mission into an arbitrary number of segments, where each segment consists of several days with the daily weather vector distributed according to a segmented truncated bi-normal distribution. The power risk is thus derived through the computer simulation of 10,000 pseudo-missions, which consist of daily weather vectors according to known specific and segmented truncated bi-normal distributions. A pseudo-mission is only considered to be successful if all weather vectors fall outside the critical region. For selecting a suitable ice-class for the MV-Bluefin vessel to operate in the polar areas, recommendations from DNV cold climate expertise should be considered. However, recommended ice-class notations can be used for the MV-Bluefin Research Vessel developed by DNV to mitigate unwanted risks and several issues highlighted in this study.

Furthermore, this thesis has provided recommendations for the operation of vessels in harsh climates in light of the findings that the delicate elements involved in the vessel's operation in polar regions may adversely be affected by salinity and both ambient air temperature and seawater temperature. As such, a numerical model was developed to estimate the vessel's energy requirement to maintain an internal ambient temperature suitable for both the success of the mission and the safeguarding of lives. It was subsequently demonstrated that the MV-Bluefin is adversely affected by SW and air temperature which is ill-equipped to ensure safe passage throughout the polar region, being incapable of exerting the required 225kW to maintain a safe 18°C internal temperature, as well as the 25W to operate the SWCS safely, the 50W to maintain the LOS, the 25.75W to ensure adequate fuel viscosity in the FOS, and the 240W to ensure adequate heating of the vessel.

Therefore, this thesis has demonstrated that the MV-Bluefin is incapable of adhering to the winterisation requirements set out by the polar code or the suggestions put forward by the numerical model presented in Chapter 7 of this work. As well as identifying a number of especially complex systems, this thesis recommends immediate modification of the MV-Bluefin to enhance the vessel's safety and associated systems to preserve life in the harsh Antarctic region.

References

1. SOLAS. *International Convention for the Safety of Life at Sea (SOLAS)*. 2010 [cited 2021 5 March]; Available from: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx.
2. Julian, M., *MARPOL 73/78: the International Convention for the Prevention of Pollution from Ships.* Maritime Studies, 2000. **2000**(113): p. 16-23.
3. IAATO. *Report on IAATO operator use of Antarctic Peninsula landing sites and ATCM visitor site guidelines, 2017–18 season*. 2019 [cited 2021 5 March]; Available from: https://iaato.org/wp-content/uploads/2020/03/ATCM41_ip72_e.pdf.
4. Dastidar, P.G. and Persson, O., *Mapping the global structure of Antarctic research vis-à-vis Antarctic Treaty System.* Current Science, 2005. **89**(9): p. 1552-1560.
5. Deggim, H., *The international code for ships operating in polar waters (Polar Code)*, in *Sustainable shipping in a changing Arctic*. 2018, Springer, Cham: Hildebrand L., Brigham L., Johansson T. p. 15-35.
6. IMO, *Guidelines for Ships Operating in Polar Waters* Vol. 40. 2010: International Maritime Organization.
7. Dolny, J., et al., *Developing a Technical Methodology for the Evaluation of Safe Operating Speeds in Various Ice Conditions*, in *22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'13)*. 2013, Port and Ocean Engineering under Arctic Conditions (POAC): Espoo, Finland. p. 13.
8. Jabour, J., *Progress towards the mandatory code for polar shipping.* Australian Journal of Maritime & Ocean Affairs, 2014. **6**(1): p. 64-67.
9. Bai, J., *The IMO Polar Code: The emerging rules of Arctic shipping governance.* The International Journal of Marine and Coastal Law, 2015. **30**(4): p. 674-699.
10. Fedi, L., et al., *Arctic Navigation: Stakes, Benefits and Limits of the Polaris System.* The Journal of Ocean Technology, 2018. **13**(4): p. 54-67.
11. Deggim, H., *International Requirements for Ships Operating in Polar Waters*, in *Meeting of experts on the management of ship-borne tourism in the Antarctic Treaty Area*. 2009, International Maritime Organization (IMO): Wellington, New Zealand. p. 1-15.
12. ITF. *STCW: A Guide For Seafares - Taking into account the 2010 Manila amendments*. STCW: A Guide For Seafares - Taking into account the 2010 Manila amendments, Number of 78 2010 [cited Access 2010; Available from: https://www.mptusa.com/pdf/STCW_guide_english.pdf.
13. I-, A., *Regukations for the Prevention of Pollution by Oil* entered into force 2 October 1983.
14. Wang, Y. and Ho Lee, W. *Polar Code and Winterization: DNV GL Annual Technology Seminar*. Polar Code and Winterization: DNV GL Annual Technology Seminar, Number of 1-117 2018 [cited Access 2018 5 Mar 2021]; Available from: https://www.dnvgl.us/Images/PolarCode_tcm14-132646.pdf.
15. Jabour, J., *Southern Ocean search and rescue: platforms and procedures*, in *Handbook on the Politics of Antarctica*. 2017, Edward Elgar Publishing: Cheltenham, UK. p. 392–407.
16. Jensen, Ø., *Arctic shipping guidelines: towards a legal regime for navigation safety and environmental protection?* The Polar Record, 2008. **44**(2): p. 107.
17. Ellis, B. and Brigham, L., *Arctic marine shipping assessment 2009 report.* 2009.
18. Davis, P.B., *Beyond guidelines: a model for Antarctic tourism.* Annals of tourism research, 1999. **26**(3): p. 516-533.

19. Bartenstein, K., *Navigating the Arctic: The Canadian NORDREG, the International Polar Code and Regional Cooperation.* German YB Int'l L, 2011. **54**: p. 77-124.
20. Peters, G., et al., *Future emissions from shipping and petroleum activities in the Arctic.* Atmospheric Chemistry and Physics, 2011. **11**(11): p. 5305-5320.
21. Inspectorate, H.E.a.T. *Polar Code (A.1024(26) Ships operating in polar waters)*. 2021 [cited 2021 5 March]; Available from: https://puc.overheid.nl/nsi/doc/PUC_1503_14/2/.
22. Grafton, T., Humphrey, R., and Nyseth, H. *The safety of government operated ships in Antarctic waters*. in *Pacific 2013 International Maritime Conference: The commercial maritime and naval defence showcase for the Asia Pacific*. 2013. Engineers Australia.
23. Harsem, Ø., Eide, A., and Heen, K., *Factors influencing future oil and gas prospects in the Arctic.* Energy policy, 2011. **39**(12): p. 8037-8045.
24. Lindholt, L. and Glomsrød, S., *The Arctic: No big bonanza for the global petroleum industry.* Energy Economics, 2012. **34**(5): p. 1465-1474.
25. DNV. *Heavy fuel in the Arctic (Phase 1)*. Heavy fuel in the Arctic (Phase 1), Number of 1-61 2011 [cited Access 2011 3 Mar 2021]; Available from: https://www.pame.is/document-library/shipping-documents/heavy-fuel-oil-documents/359-hfo-in-the-arctic-phase-i/file.
26. Jakobsen, U., *Climate Change and Risk Management Challenges in the Arctic*, in *ECPR General Conference 2015*. 2015, The European Consortium for Political Research (ECPR): Montreal, Canada. p. 29.
27. Blanco-Bazán, A., *Specific Regulations for Shipping and Environmental Protection in the Arctic: The Work of the International Maritime Organization.* The International Journal of Marine and Coastal Law, 2009. **24**(2): p. 381-386.
28. Solberg, K.E., Gudmestad, O.T., and Kvamme, B.O. *SARex Spitzbergen: Search and rescue exercise conducted off North Spitzbergen: Exercise report*. SARex Spitzbergen: Search and rescue exercise conducted off North Spitzbergen: Exercise report, Number of 1-244 2016 [cited Access 2016 1 Mar 2021]; Available from: https://uis.brage.unit.no/uis-xmlui/handle/11250/2414815.
29. Parry, M. *Australian icebreaker runs aground Antarctica*. 2016 [cited 2021 5 March]; Available from: https://phys.org/news/2016-02-australian-icebreaker-aground-antarctica.html.
30. Program, A.A. *Sir Douglas Mawson (1882 to 1958)*. 2019 [cited 2021 5 March]; Available from: https://www.antarctica.gov.au/about-antarctica/history/people/douglas-mawson/.
31. Insight, M. *What Is an Ice Breaker Ship and How Does It Work*. 2019 [cited 2021 5 March]; Available from: https://www.marineinsight.com/types-of-ships/how-does-an-ice-breaker-ship-works/.
32. GlobalSecurity. *Early Icebreakers*. 2019 [cited 2021 5 March]; Available from: https://www.globalsecurity.org/military/world/russia/icebreaker-1.htm.
33. Spaces, M. *Fuel oil system for a marine diesel engine*. 2020 [cited 2021 5 March]; Available from: http://www.machineryspaces.com/fuel-oil-system.html.
34. Ta, T., et al. *Assesment of Marine Propulsion System Reliability Based on Fault Tree Analysis*. 2017.
35. WHOI. *Early Icebreakers (20th century)*. Early Icebreakers (20th century), Number of 2007 [cited Access 2007; Available from: https://www.whoi.edu/page.do?pid=66599.
36. iStockPhoto. *Canceled Soviet Russia Postage Stamp Icebreaker Ship Arctic Ocea*. 2020 [cited 2021 5 March]; Available from: https://www.istockphoto.com/photo/canceled-soviet-russia-postage-stamp-icebreaker-ship-arctic-ocean-ice-gm152544988-13504835.

37. Cool-Antarctica. *Ernest Shackleton (1874-1922) British Antarctic Expedition Nimrod - 1907-1909*. [cited 2021 5 March]; Available from: https://www.coolantarctica.com/Antarctica%20fact%20file/History/Ernest%20Shackleton_Nimrod_expedition.php#:~:text=Shackleton%20was%20chosen%20to%20be,Zealand%20on%20August%207th%201907.
38. Division, A.A. *Australian government, Department of Agriculture*. 2019 [cited 2021 5 March]; Available from: www.antarctica.gov.au.
39. Cermany, R.i. *Research vessel Polarstern*. 1982 [cited 2021 5 March]; Available from: https://www.research-in-germany.org/en/research-landscape/research-organisations/research-infrastructures/research-vessel-polarstern.html.
40. Program, A.A. *Australia's new Antarctic icebreaker-RSV Nuyina*. 2019 [cited 2021 5 March]; Available from: https://www.antarctica.gov.au/antarctic-operations/travel-and-logistics/ships/icebreaker/.
41. Chen, L. *Chinese polar research ship damaged after hitting iceberg in Antarctica*. 10738848 2019 [cited 2021 5 March]; Available from: https://www.scmp.com/news/china/science/article/3123623/china-enters-heavy-rocket-race-planned-100-tonne-launch-vehicle.
42. Trevithick, J. *U.S.Heavy Icebreaker Is Falling Apart On Antarctic Mission*. 2018 [cited 2021 5 March]; Available from: https://www.thedrive.com/the-war-zone/18385/only-u-s-heavy-icebreaker-is-falling-apart-on-antarctic-mission.
43. EMSA. *EMSA annual overview of marine casualties and incidents* EMSA annual overview of marine casualties and incidents Number of 1-163 2019 [cited Access 2019; Available from: https://www.iims.org.uk/wp-content/uploads/2019/11/EMSA-Annual-Overview-of-Marine-Casualties-and-Incidents-2019.pdf.
44. EMSA. *Annual Overview of Marine Casualties and Incidents* Annual Overview of Marine Casualties and Incidents Number of 1-147 2020 [cited Access 2020; Available from: http://www.emsa.europa.eu/we-do/safety/accident-investigation/item/4266-annual-overview-of-marine-casualties-and-incidents-2020.html.
45. Donehue, K.J., *Shipping Governance in the Polar Regions: the Interaction of Global, Regional and National Regimes*, in *Faculty of Law*. 2018, UiT The Arctic University of Norway: Tromsø, Norway. p. 1-69.
46. Dawson, J., Johnston, M.E., and Stewart, E.J., *Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change.* Ocean & Coastal Management, 2014. **89**: p. 88-99.
47. Noroozi, A., et al., *Effects of cold environments on human reliability assessment in offshore oil and gas facilities.* Human factors, 2014. **56**(5): p. 825-839.
48. Anish. *Safety of Life at Sea (SOLAS) – The Ultimate Guide*. 1974 [cited 2021 5 Jan]; Available from: https://www.marineinsight.com/maritime-law/safety-of-life-at-sea-solas-convention-for-prevention-of-marine-pollution-marpol-a-general-overview/.
49. (IMO), I.M.O. *International Convention for the Safety of Life at Sea (SOLAS), 1974*. International Convention for the Safety of Life at Sea (SOLAS), 1974, Number of 2020 [cited Access 2020; Available from: www.imo.org.
50. McDorman, T.L., *A note on the potential conflicting treaty rights and obligations between the IMO's Polar Code and Article 234 of the Law of the Sea Convention*, in *International law and politics of the Arctic Ocean: Essays in honor of Donat Pharand*. 2015, Brill | Nijhoff. p. 141-159.
51. IMO. *Port State Control (PSC)- International Maritime Organization*. 2019 [cited 2021 5 March]; Available from: https://www.imo.org/en/OurWork/MSAS/Pages/PortStateControl.aspx.

52. Hebbar, A.A., et al., *The IMO Regulatory Framework for Arctic Shipping: Risk Perspectives and Goal-Based Pathways*, in *Governance of Arctic Shipping: Rethinking Risk, Human Impacts and Regulation*, A. Chircop, et al., Editors. 2020, Springer International Publishing: Cham. p. 229-247.
53. IMO. *Maritime Safety Committee 86th seession, DE 52-21 paragraph 9.6, 9.31-9.32*. Maritime Safety Committee 86th seession, DE 52-21 paragraph 9.6, 9.31-9.32, Number of 16 April 2009 [cited Access 16 April 2009.
54. SCAR. *Science - The Scientific Committee on Antarctic Research*. 2019 [cited 2021 5 March]; Available from: https://www.scar.org/science/.
55. Ultra-Therm. *Heat Exchangers ,PHE*. 2020 [cited 2021 5 March]; Available from: http://ultra-therm.com.au/?gclid=Cj0KCQiAvvKBBhCXARIsACTePW-66bLiJ0QtoTYUdO45OEJFJ8kha19m_oo4caorGnwsVQ7Ktza0WsUaAo_PEALw_wcB.
56. ATCM. *Final Report of the Twenty-Seventh Antarctic Treaty Consultative Meeting*. Final Report of the Twenty-Seventh Antarctic Treaty Consultative Meeting, Number of 1-483 2004 [cited Access 2004 2 Mar 2021]; Available from: https://www.asoc.org/storage/documents/Meetings/ATCM/XXVII/2004%20final%20report.pdf.
57. LIMA. *Report of Investigation in the Matter of Sinking of Passenger Vessel EXPLORER*. Report of Investigation in the Matter of Sinking of Passenger Vessel EXPLORER, Number of 1-97 2007 [cited Access 2007 5 Mar 2021]; Available from: http://www.photobits.com/dl/Explorer%20-%20Final%20Report.PDF.
58. Stewart, E. and Draper, D., *The Sinking of the M.S. Explorer: Implications for Cruise Tourism in Arctic Canada.* Arctic, 2008. **61**: p. 224-228.
59. mariners, D.e.f.P.I. *Restricted Class 6-Master/Engineer SPC 022B*. Restricted Class 6-Master/Engineer SPC 022B, Number of 1-16 2019 [cited Access 2019 2 Mar 2021]; Available from: https://spccfpstore1.blob.core.windows.net/digitallibrary-docs/files/23/23e06da86f1ee89e80f8a4219f16fefe.pdf?sv=2015-12-11&sr=b&sig=vTFLTfa%2FM9Ktmy2mEQygWvIZNN%2FlmL9YHa39dyw2ScY%3D&se=2021-08-28T16%3A21%3A51Z&sp=r&rscc=public%2C%20max-age%3D864000%2C%20max-stale%3D86400&rsct=application%2Fpdf&rscd=inline%3B%20filename%3D%22diesel_lg.pdf%22.
60. Veritas, D.N. *Report. Heavy fuel in the Arctic (Phase 1)*. Report. Heavy fuel in the Arctic (Phase 1), Number of 2011 [cited Access 2011.
61. Banda, O.A.V., et al., *Risk management model of winter navigation operations.* Marine pollution bulletin, 2016. **108**(1-2): p. 242-262.
62. Yun, G. and Marsden, A., *Methodology for estimating probability of success of Escape, Evacuation, and Rescue (EER) strategies for arctic offshore facilities.* Cold regions science and technology, 2010. **61**(2-3): p. 107-115.
63. Baen, P. and Oldford, D. *Surface heating for Arctic vessels and structures to prevent snow and ice accumulation*. in *2014 Petroleum and Chemical Industry Conference Europe*. 2014. IEEE.
64. Leonardi, J., et al. *The impacts of globalisation on international road and rail freight transport activity: past trends and future perspectives*. in *OECD/ITF Global Forum on Sustainable Development: Transport and Environment in a Globalising World*. 2008.
65. Jensen, Ø., *Arctic shipping guidelines: towards a legal regime for navigation safety and environmental protection?* Polar Record, 2008. **44**(2): p. 107-114.

66. Solesvik, M., *Exploitation of Compressed Natural Gas Carrier Ships in the High North*, in *Engineering Assets and Public Infrastructures in the Age of Digitalization*. 2020, Springer. p. 46-54.
67. Jeong, S.-Y., Lee, C.-J., and Cho, S.-R., *A Study on Anti-Icing Technique for Ballast Water of Icebreaking Vessels Operating in Ice-Covered Water*. Journal of the Society of Naval Architects of Korea, 2011. **48**.
68. Kum, S. and Sahin, B., *A root cause analysis for Arctic Marine accidents from 1993 to 2011*. Safety science, 2015. **74**: p. 206-220.
69. Timeanddate. *Climate & Weather Averages in Ushuaia, Tierra del Fuego, Argentina*. 1985-2015 [cited 2021 5 March]; Available from: https://www.timeanddate.com/weather/argentina/ushuaia/climate.
70. Timeanddate. *Climate & Weather Averages in Stanley, Falkland Islands*. 2005-2015 [cited 2021 5 March]; Available from: https://www.timeanddate.com/weather/falkland/stanley/climate.
71. Weather&Climate. *Climate in Grytviken, South Georgia*. 2019 [cited 2021 5 March]; Available from: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Grytviken,South-Georgia.
72. Holiday-Weather. *Ushuaia, Argentina: Annual Weather Averages*. 2019 [cited 2021 5 March]; Available from: https://www.holiday-weather.com/ushuaia/averages/.
73. Spark, W. *Average Weather at Mount Pleasant Airport Falkland Islands*. 2019 [cited 2021 5 March]; Available from: https://weatherspark.com/y/147511/Average-Weather-at-Mount-Pleasant-Airport-Falkland-Islands-Year-Round.
74. Spark, W. *Humidity over the year in Grytviken, South Georgia*. 2019 [cited 2021 5 March]; Available from: https://weatherspark.com/y/31225/Average-Weather-in-Grytviken-South-Georgia-&-South-Sandwich-Islands-Year-Round.
75. Spark, W. *Average Weather in Grytviken South Georgia & South Sandwich Islands*. 2019 [cited 2021 5 March]; Available from: https://weatherspark.com/y/31225/Average-Weather-in-Grytviken-South-Georgia-&-South-Sandwich-Islands-Year-Round.
76. SeasonsYear. *South Georgia and the South Sandwich Islands: Seasons and Climate*. 1996 [cited 2021 5 March]; Available from: www.seasonsyear.com.
77. SeasonsYear. *Seasons in the Antarctic Peninsula*. 2019 [cited 2021 5 March]; Available from: https://seasonsyear.com/Antarctic%20Peninsula#content-1.
78. Schwerdtfeger, W., *The Effect of the Antarctic Peninsula on the Temperature Regime of the Weddell Sea.* Monthly Weather Review, 1975. **103**(1): p. 45-51.
79. Spark, W. *Average Weather at Mount Pleasant Airport Falkland Islands*. Average Weather at Mount Pleasant Airport Falkland Islands, Number of 2019 [cited Access 2019; Available from: https://weatherspark.com › Falkland Islands.
80. Timeanddate. *Climate & Weather Averages in Hughes Peninsula, Antarctica*. 1985-2015 [cited 2021 5 March]; Available from: https://www.timeanddate.com/weather/@6635268/climate.
81. Weather&Climate. *Climate in Ushuaia (Tierra del Fuego), Argentina: Average Weather*. 2019 [cited 2021 accessed 28 Feb]; Available from: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Ushuaia,Argentina.
82. AS, T.a.D. *Climate & Weather Averages in Ushuaia, Tierra del Fuego, Argentina*. 1985-2015; Available from: www.timeanddate.com.
83. Young, I.R. and Ribal, A., *Multiplatform evaluation of global trends in wind speed and wave height.* Science, 2019. **364**(6440): p. 548-552.
84. Young, I.R., et al., *The Wave Climate of the Southern Ocean.* Journal of Physical Oceanography, 2020. **50**(5): p. 1417-1433.

85. McCarthy, A.H., et al., *Antarctica: The final frontier for marine biological invasions.* Global Change Biology, 2019. **25**(7): p. 2221-2241.
86. CCAMLR, *Report of the Working Group on Ecosystem Monitoring and Management*, in *2016 meeting of Working Group on Ecosystem Monitoring and Management*. 2016, Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR): Bologna, Italy. p. 150.
87. Hughes, K.A., et al., *Impact of anthropogenic transportation to Antarctica on alien seed viability.* Polar Biology, 2010. **33**(8): p. 1125-1130.
88. Farreny, R., et al., *Carbon dioxide emissions of Antarctic tourism.* Antarctic Science, 2011. **23**(6): p. 556-566.
89. Atkins-Davis, C., *Analyzing the Role of Vessel-Based Tourism on Masking on Antarctic Humpback Whales: A Petition for Management Solutions for Underwater Noise and Regulation of Antarctic Tourism*, in *Nicholas School of the Environment*. 2019, Duke University: Durham, NC p. 30.
90. Nelson, D.M., et al., *Vertical budgets for organic carbon and biogenic silica in the Pacific sector of the Southern Ocean, 1996–1998.* Deep Sea Research Part II: Topical Studies in Oceanography, 2002. **49**(9-10): p. 1645-1674.
91. Broecker, W.S., Takahashi, T., and Takahashi, T., *Sources and flow patterns of deep-ocean waters as deduced from potential temperature, salinity, and initial phosphate concentration.* Journal of Geophysical Research: Oceans, 1985. **90**(C4): p. 6925-6939.
92. Sverdrup, H.U., Johnson, M.W., and Fleming, R.H., *The Oceans, Their physics, chemistry, and general biology*. 1942, New York: Prentice-Hall 1087.
93. Steadman, R.G., *Indices of windchill of clothed persons.* Journal of Applied Meteorology, 1971. **10**(4): p. 674-683.
94. Makkonen, L., *Salinity and growth rate of ice formed by sea spray.* Cold Regions Science and Technology, 1987. **14**(2): p. 163-171.
95. Zakrzewski, W.P., Lozowski, E.P., and Muggeridge, D., *Estimating the extent of the spraying zone on a sea-going ship.* Ocean engineering, 1988. **15**(5): p. 413-429.
96. IACS. *Classification societies – what, why and how*. 2018 [cited 2021 5 March]; Available from: www.iacs.org.uk.
97. Quora. *Why is marine insurance important?* . 2019 [cited 2021 5 March]; Available from: www.quora.com.
98. EduMaritime. *What are the STCW Requirements for Chief Engineer?* 2019 [cited 2021 5 March]; Available from: www.edumaritime.net
99. EduMritime. *What are the STCW Requirements for Second Engineer*. 2019; Available from: www.edumaritime.net.
100. EduMaritime. *What are the STCW Requirements for Second Engineer?* 2019 [cited 2021 5 March]; Available from: www.edumaritime.net.
101. EduMaritime. *STCW III/3 - Chief Engineer and Second Engineer 750 to 3000 kW*. 2019 [cited 2021 5 March]; Available from: www.edumaritime.net
102. EduMaritime. *General Requirements for Officers (Deck and Engine)* 2019 [cited 2021 5 March]; Available from: www.edumaritime.net.
103. EduMaritime. *What are the STCW Requirements for Master Mariner?* 2019 [cited 2021 5 March]; Available from: www.edumaritime.net.
104. EduMaritime. *What are the STCW Requirements for Chief Officer (Mate) C/M*. 2019 [cited 2021 5 March]; Available from: www.edumaritime.
105. EduMaritime. *What are the STCW Requirements for Second Officer*. 2019 [cited 2021 5 March]; Available from: www.edumaritime.net.

106. Baylon, A.M. and Santos, E.M.R., *The challenges in Philippine maritime education and training.* International Journal of Innovative Interdisciplinary Research, 2011. **1**(1): p. 34-43.
107. Authority, A.S.Q. *Requirements and responsibilities*. [cited 2021 5 March]; Available from: www.asqa.gov.au
108. Centre, T.M.I.K. *Ships' Agents*. 2019 [cited 2021 5 March]; Available from: www.maritimeinfo.org.
109. Charterer, S. *Maritime Industry Knowlage Center*. 2019 [cited 2021 5 March]; Available from: www.maritimeinfo.org.
110. Investopedia. *International Maritime Organization (IMO)*. International Maritime Organization (IMO), Number of 2019 [cited Access 2019; Available from: https://www.investopedia.com › Economy › Government & Policy.
111. Olmer, N., et al. *Greenhouse Gas Emissions from Global Shipping, 2013-2015*. Greenhouse Gas Emissions from Global Shipping, 2013-2015, Number of 1-38 2017 [cited Access 2017; Available from: www.theicct.org.
112. Shanshan, F., et al., *A quantitative approach for risk assessment of a ship stuck in ice in Arctic waters.* 2017.
113. Beveridge, L., et al., *Interest of Asian shipping companies in navigating the Arctic.* Polar Science, 2016. **10**(3): p. 404-414.
114. AS, D.N.V.D.G. *Ships for navigation in ice*. Ships for navigation in ice, Number of 1-162 2016 [cited Access 2016; Available from: www.dnvgl.com.
115. DNV. *Winterization for cold climate operations*. Winterization for cold climate operations, Number of 1-87 2015 [cited Access 2015 3 Mar 2021]; Available from: https://rules.dnvgl.com/docs/pdf/dnvgl/os/2015-07/dnvgl-os-a201.pdf.
116. DNV. *IMO Polar Code* IMO Polar Code Number of 2019 [cited Access 2019; Available from: www.dnvgl.com.
117. Cicek, K., et al. *Risk-based preventive maintenance planning using Failure Mode and Effect Analysis (FMEA) for marine engine systems*. in *2010 Second International Conference on Engineering System Management and Applications*. 2010. IEEE.
118. Matthews, J., *Some aspects of circulation along the Alaskan Beaufort Sea coast*, in *Coastal Oceanography*. 1983, Springer: New York. p. 475-497.
119. Ait Allal, A., et al., *Toward a reliable sea water central cooling system for a safe operation of autonomous ship.* International Journal of Industrial Electronics and Electrical Engineering (IJIEEE), 2017. **5**(12): p. 108-117.
120. Matthews, R., *Comparing historical and modern methods of sea surface temperature measurement – Part 1: Review of methods, field comparisons and dataset adjustments.* Ocean Science (OS), 2013. **9**.
121. Cavallo, C. *All About Shell And Tube Heat Exchangers - What You Need To Know*. 2011 [cited 201 5 March]; Available from: https://www.thomasnet.com/articles/process-equipment/shell-and-tube-heat-exchangers/.
122. MIO. *Advantages and Disadvantages of Shell and Tube and Plate type Heat Exchangers*. 2020 [cited 2021 5 March]; Available from: https://marineengineeringonline.com/advantages-disadvantages-shell-tube-plate-type-heat-exchangers/.
123. *Model Course On Navigation In Polar Waters.* . 2020: p. 50-51.
124. Hu, Q., et al., *Model Course on Navigation in Polar Waters*. 2015.
125. ABS. *IMO Polar Code Advisory*. IMO Polar Code Advisory, Number of 1-68 2016 [cited Access 2016 28 Feb 2021]; Available from: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Polar_Code_Advisory_15239.pdf.

126. Heikkilä, T. and Hakanen, E. *Alternative Winterization Design Philosophy for Ships Operating in Polar Waters*. in *The 27th International Ocean and Polar Engineering Conference*. 2017. International Society of Offshore and Polar Engineers.
127. AMC. *MV-BlueFin Quality Manual* MV-BlueFin Quality Manual Number of 293 2010 [cited Access 2010 28 Feb 2021]; Available from: https://seatracker.ru/viewtopic.php?t=4960.
128. Grafton, T., Humphrey, R., and Nyseth, H. *The safety of government operated ships in Antarctic waters*. in *Proceeding of Pacific 2013 International Maritime Conference: The commercial maritime and naval defence showcase for the Asia Pacific*. 2013. Engineers Australia.
129. DNV. *Taking a broader view*. Taking a broader view, Number of 1-104 2013 [cited Access 2013 8 Mar 2021]; Available from: http://production.presstogo.com/fileroot6/gallery/dnvgl/files/original/3398a65ccc8043b48b13004f89f1cd23/3398a65ccc8043b48b13004f89f1cd23_low.pdf.
130. Oertling, T.J., *Ships' Bilge Pumps: A History of Their Development, 1500-1900*. 1996: Texas A&M University Press.
131. Van Ta, T., et al., *Assesment of Marine Propulsion System Reliability Based on Fault Tree Analysis*. International Journal of Transportation Engineering and Technology, 2016. **2**(4): p. 55-61.
132. Liberacki, R., *Influence of Redundancy and Ship Machinery Crew Manning on Reliability of Lubricating oil System for the Mc-Type Diesel Engine*. Journal of POLISH CIMAC, 2007. **2**(2): p. 129-136.
133. Sunder, S., *Thermodynamic and heat transfer modeling of a scroll pump*. 1997, Massachusetts Institute of Technology.
134. Cengel, Y.A., *Introduction to thermodynamics and heat transfer*. Vol. 846. 1997: McGraw-Hill New York.
135. Coetzee, R.A.M., Mwesigye, A., and Huan, Z., *A numerical model for optimal receiver array and mass flow rate in residential solar water heating systems*. International Journal of Sustainable Energy, 2018. **37**(9): p. 902-918.
136. Ayyub, B.M., Karaszewski, Z., and Wade, M., *Probabilistic risk analysis of diesel power generators onboard ships*. Naval engineers journal, 1999. **111**(3): p. 35-58.
137. Lu, J., et al., *Numerical study on heat and mass transfer characteristics of the counter-flow heat-source tower (CFHST)*. Energy and Buildings, 2017. **145**: p. 318-330.
138. Pelczar, R., *Lubrication Systems For Speed Increasers Used In Hydrogenerating Applications*. l4* ITERPOH/ER, 1993.
139. Fabbrocino, G., et al., *Quantitative risk analysis of oil storage facilities in seismic areas*. Journal of Hazardous Materials, 2005. **123**(1-3): p. 61-69.
140. Athienitis, A. and Ramadan, H., *Numerical model of a building with transparent insulation*. Solar Energy, 1999. **67**(1-3): p. 101-109.
141. French, S., *Decision theory: an introduction to the mathematics of rationality*. 1986: Halsted Press.
142. Duda, R.O., Hart, P.E., and Stork, D.G., *Pattern classification second edition john wiley & sons*. New York, 2001. **58**: p. 16.
143. Fukunaga, K., *Introduction to statistical pattern recognition*. 2013: Elsevier.
144. Hertz, D.B. and Thomas, H., *Risk analysis and its applications*. 1983.
145. Nikolova, N.D. and Tenekedjiev, K.I., *Fuzzy rationality and parameter elicitation in decision analysis*. International Journal of General Systems, 2010. **39**(5): p. 539-556.

Appendix A: Power Demand and Supply

```
function [SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Code_m] =
Power_demand_supply(flagplot)
% Power_demand_supply calculates the pawer deman and the power supply of
winterize Bluefin
%
% [SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Code_m] =
Power_demand_supply(flagplot)

    % Units
    Power_Unit_str='kW';
    Temperature_Unit_str='deg C';
    % Power Supply
    NumGen=2;
    PowerOneGen=86;
    PowerSupply=NumGen*PowerOneGen;
    % Power Demand
    SeawaterT_v=[-2 0 4 6 8 10 12]';
    AirT_v=[-27 -22 -18 -15 -10 -5 0];
    nsT=length(SeawaterT_v);
    maT=length(AirT_v);
    SeawaterT_m=SeawaterT_v*ones(1,maT);
    AirT_m=ones(nsT,1)*AirT_v;
    PowerDemand_total_m=zeros(nsT,maT);
    % Cooling Seawater System
    PDcss_sT_v=[13.79 13.79 12.96 11.40 9.772 9.760 7.208]';
    PDcss_m=PDcss_sT_v*ones(1,maT);
    PowerDemand_total_m=PowerDemand_total_m+PDcss_m;
    % Lubrication Oil System
    PDlos_sT_v=[27.58 27.58 25.93 22.81 19.55 19.52 14.42]';
    PDlos_m=PDlos_sT_v*ones(1,maT);
    PowerDemand_total_m=PowerDemand_total_m+PDlos_m;
    % Fuel Oil System
    PDfos_sT_v=[6.012 6.012 5.651 4.969 4.260 4.225 3.142]';
    PDfos_m=PDfos_sT_v*ones(1,maT);
    PowerDemand_total_m=PowerDemand_total_m+PDfos_m;
    % Accommodation Isulation System
    PDais_aT_v=[90.55 75.11 66.84 55.25 47.37 47.31 34.93];
    PDais_m=ones(nsT,1)*PDais_aT_v;
    PowerDemand_total_m=PowerDemand_total_m+PDais_m;
    % Costant Demand Consumers
    PDcdc=51.11;
    PDcdc_m=PDcdc*ones(nsT,maT);
    PowerDemand_total_m=PowerDemand_total_m+PDcdc_m;
    % Air Demand Consumers
    PDadc_aT_v=[25.41 24.29 23.03 21.93 20.75 19.73 18.62];
    PDadc_m=ones(nsT,1)*PDadc_aT_v;
    PowerDemand_total_m=PowerDemand_total_m+PDadc_m;
    % Seawater Demand Consumers
    PDsdc_sT_v=[31.5 31.5 30.15 29.56 28.78 27.65 26.43]';
    PDsdc_m=PDsdc_sT_v*ones(1,maT);
    PowerDemand_total_m=PowerDemand_total_m+PDsdc_m;
    % Code calculation
    Code_m=PowerDemand_total_m<=PowerSupply;
    % Type Output
    if flagplot==1
        clc;
        for i=1:nsT
            for j=1:maT
```

```
                disp(' ');
                fprintf(1,'Conditions: Seawater Temperature=%.1f %s & Air
Temperature=%.1f %s\n'...

,SeawaterT_m(i,j),Temperature_Unit_str,AirT_m(i,j),Temperature_Unit_str);
                fprintf(1,'Power Demand=%.0f %s & Power Supply=%.0f
%s\n'...

,PowerDemand_total_m(i,j),Power_Unit_str,PowerSupply,Power_Unit_str);
                if Code_m(i,j)
                    fprintf(1,'The Power Supply is enough to satify the
Power Demand\n');
                else
                    fprintf(1,'Failure: the Power Supply is not enough to
satify the Power Demand\n');
                end
            end
        end
    end
end
```

>>[SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Code_m]…

= Power_demand_supply(1)

```
Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-27.0 deg C
Power Demand=246 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-22.0 deg C
Power Demand=229 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-18.0 deg C
Power Demand=220 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-15.0 deg C
Power Demand=207 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-10.0 deg C
Power Demand=198 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=-5.0 deg C
Power Demand=197 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=-2.0 deg C & Air Temperature=0.0 deg C
Power Demand=184 kW & Power Supply=172 kW
```

Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-27.0 deg C
Power Demand=246 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-22.0 deg C
Power Demand=229 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-18.0 deg C
Power Demand=220 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-15.0 deg C
Power Demand=207 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-10.0 deg C
Power Demand=198 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=-5.0 deg C
Power Demand=197 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=0.0 deg C & Air Temperature=0.0 deg C
Power Demand=184 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-27.0 deg C
Power Demand=242 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-22.0 deg C
Power Demand=225 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-18.0 deg C
Power Demand=216 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-15.0 deg C
Power Demand=203 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-10.0 deg C
Power Demand=194 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=-5.0 deg C
Power Demand=193 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=4.0 deg C & Air Temperature=0.0 deg C
Power Demand=179 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-27.0 deg C
Power Demand=236 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-22.0 deg C
Power Demand=219 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-18.0 deg C
Power Demand=210 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-15.0 deg C
Power Demand=197 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-10.0 deg C
Power Demand=188 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=-5.0 deg C
Power Demand=187 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=6.0 deg C & Air Temperature=0.0 deg C
Power Demand=173 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-27.0 deg C
Power Demand=229 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-22.0 deg C
Power Demand=213 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-18.0 deg C
Power Demand=203 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-15.0 deg C
Power Demand=191 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-10.0 deg C
Power Demand=182 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=-5.0 deg C
Power Demand=181 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=8.0 deg C & Air Temperature=0.0 deg C
Power Demand=167 kW & Power Supply=172 kW
The Power Supply is enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-27.0 deg C
Power Demand=228 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-22.0 deg C
Power Demand=212 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-18.0 deg C
Power Demand=202 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-15.0 deg C
Power Demand=189 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-10.0 deg C
Power Demand=180 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=-5.0 deg C

```
Power Demand=179 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=10.0 deg C & Air Temperature=0.0 deg C
Power Demand=166 kW & Power Supply=172 kW
The Power Supply is enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-27.0 deg C
Power Demand=218 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-22.0 deg C
Power Demand=202 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-18.0 deg C
Power Demand=192 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-15.0 deg C
Power Demand=179 kW & Power Supply=172 kW
Failure: the Power Supply is not enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-10.0 deg C
Power Demand=170 kW & Power Supply=172 kW
The Power Supply is enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=-5.0 deg C
Power Demand=169 kW & Power Supply=172 kW
The Power Supply is enough to satify the Power Demand

Conditions: Seawater Temperature=12.0 deg C & Air Temperature=0.0 deg C
Power Demand=156 kW & Power Supply=172 kW
The Power Supply is enough to satify the Power Demand
```

Table A1. Power demand and supply as a function of the centroid of each rectangle (see section 8.2)

SI	Seawater Temp., °C	Air Temp., °C	Power Demand, kW	Power Supply, kW	Satisfy Power Demand (Y/N)
1	-2	-27	246	172	N
2	-2	-22	229	172	N
3	-2	-18	220	172	N
4	-2	-15	207	172	N
5	-2	-10	198	172	N
6	-2	-5	197	172	N
7	-2	0	184	172	N
8	0	-27	246	172	N
9	0	-22	229	172	N
10	0	-18	220	172	N
11	0	-15	207	172	N
12	0	-10	198	172	N
13	0	-5	197	172	N
14	0	0	184	172	N
15	4	-27	242	172	N
16	4	-22	225	172	N
17	4	-18	216	172	N
18	4	-15	203	172	N
19	4	-10	194	172	N
20	4	-5	193	172	N
21	4	0	179	172	N
22	6	-27	236	172	N
23	6	-22	219	172	N
24	6	-18	210	172	N
25	6	-15	197	172	N
26	6	-10	188	172	N
27	6	-5	187	172	N
28	6	0	173	172	N
29	8	-27	229	172	N
30	8	-22	213	172	N
31	8	-18	203	172	N
32	8	-15	191	172	N
33	8	-10	182	172	N
34	8	-5	181	172	N
35	8	0	167	172	Y
36	10	-27	228	172	N
37	10	-22	212	172	N
38	10	-18	202	172	N
39	10	-15	189	172	N
40	10	-10	180	172	N
41	10	-5	179	172	N
42	10	0	166	172	Y
43	12	-27	218	172	N
44	12	-22	202	172	N
45	12	-18	192	172	N
46	12	-15	179	172	N
47	12	-10	170	172	Y
48	12	-5	169	172	Y
49	12	0	156	172	Y

Appendix B: Function and Output for the First Power Risk Model

```
function [Power_risk,P_m] =
Risk_norm_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT,sig_swT,mu
_aT,sig_aT,cor_swT_aT,flagplot)
% Risk_norm_dist calculates the Power risk if the distribution is truncated bi-
normal
%
% [Power_risk,P_m] =
Risk_norm_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT,sig_swT,mu
_aT,sig_aT,cor_swT_aT,flagplot)

    % default values
    if nargin<10 || isempty(flagplot)
        flagplot=true;
    end
    if nargin<9 || isempty(cor_swT_aT)
        cor_swT_aT=0.5;
    end
    if nargin<8 || isempty(sig_aT)
        sig_aT=30;
    end
    if nargin<7 || isempty(mu_aT)
        mu_aT=-1;
    end
    if nargin<6 || isempty(sig_swT)
        sig_swT=30;
    end
    if nargin<5 || isempty(mu_swT)
        mu_swT=7;
    end
    % Units
    Power_Unit_str='kW';
    Temperature_Unit_str='deg C';
    % Formation of the rectangles
    SeawaterT_min=-2.5;
    SeawaterT_max=20;
    SeawaterT_v=SeawaterT_m(:,1);
    AirT_min=-50;
    AirT_max=30;
    AirT_v=AirT_m(1,:);
    nsT=length(SeawaterT_v);
    maT=length(AirT_v);
    SeawaterT_mar_v=[SeawaterT_min; mean([SeawaterT_v(1:(nsT-1))
SeawaterT_v(2:nsT)],2); SeawaterT_max];
    AirT_mar_v=[AirT_min mean([AirT_v(1:(maT-1)) ; AirT_v(2:maT)],1) AirT_max];
    Code_m=PowerDemand_total_m<=PowerSupply;
    % Calculation of the rectangele probabilities
    mu_v=[mu_aT;mu_swT];
    S_m=[sig_aT^2 sig_aT*sig_swT*cor_swT_aT;sig_aT*sig_swT*cor_swT_aT sig_swT^2];
    CDF_mar_v=NaN(nsT+1,maT+1);
    for i=1:(nsT+1)
        for j=1:(maT+1)
            CDF_mar_v(i,j) = mvncdf([AirT_mar_v(j);SeawaterT_mar_v(i)],mu_v,S_m);
        end
    end
    P_m=NaN(nsT,maT);
    for i=1:nsT
        for j=1:maT
            P_m(i,j)=CDF_mar_v(i+1,j+1)+CDF_mar_v(i,j)-CDF_mar_v(i+1,j)-
CDF_mar_v(i,j+1);
        end
    end
    P_m=P_m/(sum(sum(P_m)));
    % Power risk calculation
```

```
    Power_risk=1-sum(sum(P_m.*Code_m));
    % Type Output
    if flagplot==1
        clc;
        for i=1:nsT
            for j=1:maT
                disp(' ');
                fprintf(1,'Conditions:\n')
                fprintf(1,'%.1f %s<Seawater Temperature<%.1f %s\n'...

,SeawaterT_mar_v(i),Temperature_Unit_str,SeawaterT_mar_v(i+1),Temperature_Unit_str)
;
                fprintf(1,'%.1f %s<Air Temperature<%.1f %s\n'...

,AirT_mar_v(j),Temperature_Unit_str,AirT_mar_v(j+1),Temperature_Unit_str);
                fprintf(1,'Probability for the weather to be in the
rectangle=%6.3f%%\n',100*P_m(i,j));
                fprintf(1,'Power Demand=%.0f %s & Power Supply=%.0f %s\n'...

,PowerDemand_total_m(i,j),Power_Unit_str,PowerSupply,Power_Unit_str);
                if Code_m(i,j)
                    fprintf(1,'The Power Supply is enough to satisfy the Power
Demand\n');
                else
                    fprintf(1,'Failure: the Power Supply is not enough to satisfy
the Power Demand\n');
                end
            end
        end
        disp(' ');
        fprintf(1,'Power Risk=%6.3f%%\n',100*Power_risk);
    end
end
```

>>PowerSupply=220;mu_swT=7;sig_swT=30;mu_aT=-1;sig_aT=30;cor_swT_aT=0.5;flagplot=1;

>>[Power_risk,P_m]…
=Risk_norm_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT,sig_swT…
mu_aT,sig_aT,cor_swT_aT,flagplot);

```
Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Probability for the weather to be in the rectangle= 1.453%

Power Demand=246 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand


Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Probability for the weather to be in the rectangle= 0.432%

Power Demand=229 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand
```

Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-20.0 deg C<Air Temperature<-16.5 deg C

Probability for the weather to be in the rectangle= 0.367%

Power Demand=220 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Probability for the weather to be in the rectangle= 0.446%

Power Demand=207 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Probability for the weather to be in the rectangle= 0.583%

Power Demand=198 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Probability for the weather to be in the rectangle= 0.593%

Power Demand=197 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-2.5 deg C<Seawater Temperature<-1.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Probability for the weather to be in the rectangle= 2.856%

Power Demand=184 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Probability for the weather to be in the rectangle= 2.817%

Power Demand=246 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Probability for the weather to be in the rectangle= 0.856%

Power Demand=229 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-20.0 deg C<Air Temperature<-16.5 deg C

Probability for the weather to be in the rectangle= 0.732%

Power Demand=220 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Probability for the weather to be in the rectangle= 0.895%

Power Demand=207 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Probability for the weather to be in the rectangle= 1.179%

Power Demand=198 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

-1.0 deg C<Seawater Temperature<2.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Probability for the weather to be in the rectangle= 1.207%

```
Power Demand=197 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
-1.0 deg C<Seawater Temperature<2.0 deg C
-2.5 deg C<Air Temperature<30.0 deg C
Probability for the weather to be in the rectangle= 5.980%
Power Demand=184 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
2.0 deg C<Seawater Temperature<5.0 deg C
-50.0 deg C<Air Temperature<-24.5 deg C
Probability for the weather to be in the rectangle= 2.672%
Power Demand=242 kW & Power Supply=220 kW
Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:
2.0 deg C<Seawater Temperature<5.0 deg C
-24.5 deg C<Air Temperature<-20.0 deg C
Probability for the weather to be in the rectangle= 0.835%
Power Demand=225 kW & Power Supply=220 kW
Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:
2.0 deg C<Seawater Temperature<5.0 deg C
-20.0 deg C<Air Temperature<-16.5 deg C
Probability for the weather to be in the rectangle= 0.720%
Power Demand=216 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
2.0 deg C<Seawater Temperature<5.0 deg C
-16.5 deg C<Air Temperature<-12.5 deg C
Probability for the weather to be in the rectangle= 0.888%
Power Demand=203 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand
```

Conditions:

2.0 deg C<Seawater Temperature<5.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Probability for the weather to be in the rectangle= 1.181%

Power Demand=194 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

2.0 deg C<Seawater Temperature<5.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Probability for the weather to be in the rectangle= 1.224%

Power Demand=193 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

2.0 deg C<Seawater Temperature<5.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Probability for the weather to be in the rectangle= 6.288%

Power Demand=179 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

5.0 deg C<Seawater Temperature<7.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Probability for the weather to be in the rectangle= 1.688%

Power Demand=236 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:

5.0 deg C<Seawater Temperature<7.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Probability for the weather to be in the rectangle= 0.540%

Power Demand=219 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

5.0 deg C<Seawater Temperature<7.0 deg C

```
-20.0 deg C<Air Temperature<-16.5 deg C
Probability for the weather to be in the rectangle= 0.469%
Power Demand=210 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
5.0 deg C<Seawater Temperature<7.0 deg C
-16.5 deg C<Air Temperature<-12.5 deg C
Probability for the weather to be in the rectangle= 0.582%
Power Demand=197 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
5.0 deg C<Seawater Temperature<7.0 deg C
-12.5 deg C<Air Temperature<-7.5 deg C
Probability for the weather to be in the rectangle= 0.781%
Power Demand=188 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
5.0 deg C<Seawater Temperature<7.0 deg C
-7.5 deg C<Air Temperature<-2.5 deg C
Probability for the weather to be in the rectangle= 0.817%
Power Demand=187 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
5.0 deg C<Seawater Temperature<7.0 deg C
-2.5 deg C<Air Temperature<30.0 deg C
Probability for the weather to be in the rectangle= 4.329%
Power Demand=173 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-50.0 deg C<Air Temperature<-24.5 deg C
Probability for the weather to be in the rectangle= 1.607%
```

```
Power Demand=229 kW & Power Supply=220 kW
Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-24.5 deg C<Air Temperature<-20.0 deg C
Probability for the weather to be in the rectangle= 0.523%
Power Demand=213 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-20.0 deg C<Air Temperature<-16.5 deg C
Probability for the weather to be in the rectangle= 0.457%
Power Demand=203 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-16.5 deg C<Air Temperature<-12.5 deg C
Probability for the weather to be in the rectangle= 0.571%
Power Demand=191 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-12.5 deg C<Air Temperature<-7.5 deg C
Probability for the weather to be in the rectangle= 0.771%
Power Demand=182 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand

Conditions:
7.0 deg C<Seawater Temperature<9.0 deg C
-7.5 deg C<Air Temperature<-2.5 deg C
Probability for the weather to be in the rectangle= 0.812%
Power Demand=181 kW & Power Supply=220 kW
The Power Supply is enough to satisfy the Power Demand
```

Conditions:

7.0 deg C<Seawater Temperature<9.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Probability for the weather to be in the rectangle= 4.413%

Power Demand=167 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Probability for the weather to be in the rectangle= 1.520%

Power Demand=228 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Probability for the weather to be in the rectangle= 0.504%

Power Demand=212 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-20.0 deg C<Air Temperature<-16.5 deg C

Probability for the weather to be in the rectangle= 0.443%

Power Demand=202 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Probability for the weather to be in the rectangle= 0.556%

Power Demand=189 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Probability for the weather to be in the rectangle= 0.756%

Power Demand=180 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Probability for the weather to be in the rectangle= 0.802%

Power Demand=179 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

9.0 deg C<Seawater Temperature<11.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Probability for the weather to be in the rectangle= 4.473%

Power Demand=166 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Probability for the weather to be in the rectangle= 5.698%

Power Demand=218 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Probability for the weather to be in the rectangle= 1.981%

Power Demand=202 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-20.0 deg C<Air Temperature<-16.5 deg C

Probability for the weather to be in the rectangle= 1.770%

Power Demand=192 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Probability for the weather to be in the rectangle= 2.254%

Power Demand=179 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Probability for the weather to be in the rectangle= 3.120%

Power Demand=170 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Probability for the weather to be in the rectangle= 3.377%

Power Demand=169 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Conditions:

11.0 deg C<Seawater Temperature<20.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Probability for the weather to be in the rectangle=20.182%

Power Demand=156 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Table B1. Probability for the two-dimensional temperature vector to fall within each rectangle as a function of the centroid of the rectangle (see section 8.3).

SI	Seawater Temp., °C	Air Temp., °C	Probability for falling within the rectangle
1	-2	-27	0.0145
2	-2	-22	0.0043
3	-2	-18	0.0037
4	-2	-15	0.0045
5	-2	-10	0.0058
6	-2	-5	0.0059
7	-2	0	0.0286
8	0	-27	0.0282
9	0	-22	0.0086
10	0	-18	0.0073
11	0	-15	0.0089
12	0	-10	0.0118
13	0	-5	0.0121
14	0	0	0.0598
15	4	-27	0.0267
16	4	-22	0.0083
17	4	-18	0.0072
18	4	-15	0.0089
19	4	-10	0.0118
20	4	-5	0.0122
21	4	0	0.0629
22	6	-27	0.0169
23	6	-22	0.0054
24	6	-18	0.0047
25	6	-15	0.0058
26	6	-10	0.0078
27	6	-5	0.0082
28	6	0	0.0433
29	8	-27	0.0161
30	8	-22	0.0052
31	8	-18	0.0046
32	8	-15	0.0057
33	8	-10	0.0077
34	8	-5	0.0081
35	8	0	0.0441
36	10	-27	0.0152
37	10	-22	0.0050
38	10	-18	0.0044
39	10	-15	0.0056
40	10	-10	0.0076
41	10	-5	0.0080
42	10	0	0.0447
43	12	-27	0.0570
44	12	-22	0.0198
45	12	-18	0.0177
46	12	-15	0.0225
47	12	-10	0.0312
48	12	-5	0.0338
49	12	0	0.2018

Appendix C: Function and Output for the Second Power Risk Model

```
function [Power_risk] =
Risk_simulate_eval_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Npr,mu_s
wT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)
% Risk_simulate_eval_dist calculates the Power risk if the distribution is extreme
value consisting of Mdist normal distributions
%
%  [Power_risk] =
Risk_simulate_eval_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Npr,mu_s
wT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)

    % default values
    if nargin<12 || isempty(flagplot)
        flagplot=true;
    end
    if nargin<11 || isempty(n_v)
        n_v=[4; 5; 3; 2];
    end
    if nargin<10 || isempty(cor_swT_aT_v)
        cor_swT_aT_v=[.5; .6;.4;.5];
    end
    if nargin<9 || isempty(sig_aT_v)
        sig_aT_v=[5; 6 ; 6 ; 4.5];
    end
    if nargin<8 || isempty(mu_aT_v)
        mu_aT_v=[-10; -12; -8; 5];
    end
    if nargin<7 || isempty(sig_swT_v)
        sig_swT_v=[3; 4; 4.5 ;3];
    end
    if nargin<6 || isempty(mu_swT_v)
        mu_swT_v=[6 ; 4 ; 3 ;6];
    end
    nprmax=3;
    % Units
    Power_Unit_str='kW';
    Temperature_Unit_str='deg C';
    % Formation of the rectangles
    SeawaterT_min=-2.5;
    SeawaterT_max=20;
    SeawaterT_v=SeawaterT_m(:,1);
    AirT_min=-50;
    AirT_max=30;
    AirT_v=AirT_m(1,:);
    nsT=length(SeawaterT_v);
    maT=length(AirT_v);
    SeawaterT_mar_v=[SeawaterT_min; mean([SeawaterT_v(1:(nsT-1))
SeawaterT_v(2:nsT)],2); SeawaterT_max];
    AirT_mar_v=[AirT_min mean([AirT_v(1:(maT-1)) ; AirT_v(2:maT)],1) AirT_max];
    Code_m=PowerDemand_total_m<=PowerSupply;
    % Initialisation of the simulation
    Mdist=length(n_v);
    mu_c=cell(Mdist,1);
    S_c=cell(Mdist,1);
    for mdist=1:Mdist
       mu_aT=mu_aT_v(mdist);
       mu_swT=mu_swT_v(mdist);
       cov11=sig_aT_v(mdist)^2;
       cov22=sig_swT_v(mdist)^2;
       cov12=sig_aT_v(mdist)*sig_swT_v(mdist)*cor_swT_aT_v(mdist);
       mu_c{mdist}=[mu_aT;mu_swT];
       S_c{mdist}=[cov11 cov12;cov12 cov22];
    end
    YN_v=true(Npr,1);
```

```
    % simulation
    if flagplot==1
       clc;
    end
    for npr=1:Npr
        if flagplot==1 && npr<=nprmax
            disp(' ');
            fprintf(1,'Pseudo-reality #%i\n',npr);
        end
        for mdist=1:Mdist
            if flagplot==1 && npr<=nprmax
                disp(' ');
                fprintf(1,'Segment #%i (Pseudo-reality #%i)\n',mdist,npr);
            end
            n_cur=n_v(mdist);
            Data_m=NaN(n_cur,2);
            for k=1:n_cur
                while 1==1
                    wea_v=mvnrnd(mu_c{mdist},S_c{mdist});
                    if wea_v(1)<AirT_min
                    elseif wea_v(1)>AirT_max
                    elseif wea_v(2)<SeawaterT_min
                    elseif wea_v(2)>SeawaterT_max
                    else
                       Data_m(k,:)=wea_v;
                       break;
                    end
                end
            end
            i_v=interp1(SeawaterT_mar_v,(1:(nsT+1))',Data_m(:,2),'previous');
            j_v=interp1(AirT_mar_v,1:(maT+1),Data_m(:,1),'previous');
            for w=1:n_v(mdist)
                if flagplot==1 && npr<=nprmax
                    disp(' ');
                    fprintf(1,'Day #%i (Segment #%i ; Pseudo-reality
#%i)\n',w,mdist,npr);
                    fprintf(1,'Weather Conditions:\n')
                    fprintf(1,'Seawater Temperature=%.1f %s & Air Temperature=%.1f
%s\n'...

,Data_m(w,2),Temperature_Unit_str,Data_m(w,1),Temperature_Unit_str);
                    fprintf(1,'The weather vector belongs to the rectangle:\n')
                    fprintf(1,'%.1f %s<Seawater Temperature<%.1f %s\n'...

,SeawaterT_mar_v(i_v(w)),Temperature_Unit_str,SeawaterT_mar_v(i_v(w)+1),Temperature
_Unit_str);
                    fprintf(1,'%.1f %s<Air Temperature<%.1f %s\n'...

,AirT_mar_v(j_v(w)),Temperature_Unit_str,AirT_mar_v(j_v(w)+1),Temperature_Unit_str)
;
                    fprintf(1,'Power Demand=%.0f %s & Power Supply=%.0f %s\n'...

,PowerDemand_total_m(i_v(w),j_v(w)),Power_Unit_str,PowerSupply,Power_Unit_str);
                    if Code_m(i_v(w),j_v(w))
                        fprintf(1,'The Power Supply is enough to satisfy the Power
Demand\n');
                    else
                        fprintf(1,'Failure: the Power Supply is not enough to
satisfy the Power Demand\n');
                    end
                end
                if Code_m(i_v(w),j_v(w))==false
                   YN_v(npr)=false;
                   break
                end
            end
            if YN_v(npr)==false
                break
```

```
            end
        end
        if flagplot==1 && npr<=nprmax
            disp(' ');
            if YN_v(npr)==true
                fprintf(1,'No power failure in the pseudo-reality #%i\n',npr);
            elseif YN_v(npr)==false
                fprintf(1,'Power failure in the pseudo-reality #%i\n',npr);
            end
        end
    end
    Power_risk=1-sum(YN_v)/Npr;
    if flagplot==1
        disp(' ');
        fprintf(1,'Power Risk=%6.3f%%\n',100*Power_risk);
    end
end
```

```
>>PowerSupply=220;mu_swT_v=[ 6 ; 4 ; 3 ;6];sig_swT_v=[ 3; 4; 4.5 ;3];
>>mu_aT_v=[ -10; -12; -8; 5]; sig_aT_v=[ 5; 6 ; 6 ; 4.5];
>>cor_swT_aT_v=[ .5; .6;.4;.5]; c_v=[ 4; 5; 3; 2]; Npr=10000; flagplot=1;

>>[Power_risk]…
=Risk_simulate_eval_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,Npr…
,mu_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,c_v,flagplot)
```

```
Pseudo-reality #1


Segment #1 (Pseudo-reality #1)


Day #1 (Segment #1 ; Pseudo-reality #1)

Weather Conditions:

Seawater Temperature=5.6 deg C & Air Temperature=-12.8 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Power Demand=197 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand


Day #2 (Segment #1 ; Pseudo-reality #1)

Weather Conditions:

Seawater Temperature=4.9 deg C & Air Temperature=-8.0 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=194 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand
```

Day #3 (Segment #1 ; Pseudo-reality #1)

Weather Conditions:

Seawater Temperature=7.9 deg C & Air Temperature=-11.4 deg C

The weather vector belongs to the rectangle:

7.0 deg C<Seawater Temperature<9.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=182 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #4 (Segment #1 ; Pseudo-reality #1)

Weather Conditions:

Seawater Temperature=4.1 deg C & Air Temperature=-28.4 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-50.0 deg C<Air Temperature<-24.5 deg C

Power Demand=242 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Power failure in the pseudo-reality #1

Pseudo-reality #2

Segment #1 (Pseudo-reality #2)

Day #1 (Segment #1 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=4.3 deg C & Air Temperature=-13.9 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-16.5 deg C<Air Temperature<-12.5 deg C

Power Demand=203 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #1 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=8.9 deg C & Air Temperature=-4.4 deg C

The weather vector belongs to the rectangle:

7.0 deg C<Seawater Temperature<9.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=181 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #3 (Segment #1 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=7.4 deg C & Air Temperature=-6.3 deg C

The weather vector belongs to the rectangle:

7.0 deg C<Seawater Temperature<9.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=181 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #4 (Segment #1 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=10.3 deg C & Air Temperature=-7.6 deg C

The weather vector belongs to the rectangle:

9.0 deg C<Seawater Temperature<11.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=180 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Segment #2 (Pseudo-reality #2)

Day #1 (Segment #2 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=6.6 deg C & Air Temperature=-9.2 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=188 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #2 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=9.6 deg C & Air Temperature=-4.2 deg C

The weather vector belongs to the rectangle:

9.0 deg C<Seawater Temperature<11.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=179 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #3 (Segment #2 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=6.4 deg C & Air Temperature=-10.9 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=188 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #4 (Segment #2 ; Pseudo-reality #2)

Weather Conditions:

Seawater Temperature=3.0 deg C & Air Temperature=-22.1 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-24.5 deg C<Air Temperature<-20.0 deg C

Power Demand=225 kW & Power Supply=220 kW

Failure: the Power Supply is not enough to satisfy the Power Demand

Power failure in the pseudo-reality #2

Pseudo-reality #3

Segment #1 (Pseudo-reality #3)

Day #1 (Segment #1 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=8.1 deg C & Air Temperature=-1.5 deg C

The weather vector belongs to the rectangle:

7.0 deg C<Seawater Temperature<9.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Power Demand=167 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #1 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=7.0 deg C & Air Temperature=-3.4 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=187 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #3 (Segment #1 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=6.8 deg C & Air Temperature=-5.3 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=187 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #4 (Segment #1 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=6.6 deg C & Air Temperature=-16.7 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-20.0 deg C<Air Temperature<-16.5 deg C

Power Demand=210 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Segment #2 (Pseudo-reality #3)

Day #1 (Segment #2 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=5.4 deg C & Air Temperature=-10.3 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=188 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #2 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=10.9 deg C & Air Temperature=-5.1 deg C

The weather vector belongs to the rectangle:

9.0 deg C<Seawater Temperature<11.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=179 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #3 (Segment #2 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=8.3 deg C & Air Temperature=-5.3 deg C

The weather vector belongs to the rectangle:

7.0 deg C<Seawater Temperature<9.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=181 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #4 (Segment #2 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=6.5 deg C & Air Temperature=-5.0 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=187 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #5 (Segment #2 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=4.6 deg C & Air Temperature=-10.4 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=194 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Segment #3 (Pseudo-reality #3)

Day #1 (Segment #3 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=12.1 deg C & Air Temperature=-0.7 deg C

The weather vector belongs to the rectangle:

11.0 deg C<Seawater Temperature<20.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Power Demand=156 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #3 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=7.0 deg C & Air Temperature=-7.1 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-7.5 deg C<Air Temperature<-2.5 deg C

Power Demand=187 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #3 (Segment #3 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=4.2 deg C & Air Temperature=-8.5 deg C

The weather vector belongs to the rectangle:

2.0 deg C<Seawater Temperature<5.0 deg C

-12.5 deg C<Air Temperature<-7.5 deg C

Power Demand=194 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Segment #4 (Pseudo-reality #3)

Day #1 (Segment #4 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=0.9 deg C & Air Temperature=0.8 deg C

The weather vector belongs to the rectangle:

-1.0 deg C<Seawater Temperature<2.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Power Demand=184 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

Day #2 (Segment #4 ; Pseudo-reality #3)

Weather Conditions:

Seawater Temperature=6.9 deg C & Air Temperature=1.7 deg C

The weather vector belongs to the rectangle:

5.0 deg C<Seawater Temperature<7.0 deg C

-2.5 deg C<Air Temperature<30.0 deg C

Power Demand=173 kW & Power Supply=220 kW

The Power Supply is enough to satisfy the Power Demand

No power failure in the pseudo-reality #3

Appendix D: Function and Output for the Third Power Risk Model

```
function [Power_risk,Power_risk_v] =
Risk_generalized_model(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT_v,
sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)
% Risk_generalized_model analytically calculates the Power risk if the distribution
is an Extreme Value consisting of Mdist normal distributions
%
%  [Power_risk,Power_risk_v] =
Risk_generalized_model(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT_v,
sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)

    % default values
    if nargin<11
        flagplot=false;
    end
    if nargin<10  || isempty(n_v)
        n_v=[4; 5; 3; 2];
    end
    if nargin<9  || isempty(cor_swT_aT_v)
        cor_swT_aT_v=[.5; .6;.4;.5];
    end
    if nargin<8  || isempty(sig_aT_v)
        sig_aT_v=[5; 6 ; 6 ; 4.5];
    end
    if nargin<7 || isempty(mu_aT_v)
        mu_aT_v=[-10; -12; -8; 5];
    end
    if nargin<6 || isempty(sig_swT_v)
        sig_swT_v=[3; 4; 4.5 ;3];
    end
    if nargin<5 || isempty(mu_swT_v)
        mu_swT_v=[6 ; 4 ; 3 ;6];
    end
    % Initialisation of the simulation
    Mdist=length(n_v);
    Power_risk_v=NaN(Mdist,1);
    for mdist=1:Mdist
       mu_swT=mu_swT_v(mdist);
       sig_swT=sig_swT_v(mdist);
       mu_aT=mu_aT_v(mdist);
       sig_aT=sig_aT_v(mdist);
       cor_swT_aT=cor_swT_aT_v(mdist);
       Power_risk=
Risk_norm_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply,mu_swT,sig_swT,mu
_aT,sig_aT,cor_swT_aT,0);
       Power_risk_v(mdist)=Power_risk;
    end
    Power_risk=1;
    for mdist=1:Mdist
        Power_risk=Power_risk*(1- Power_risk_v(mdist)).^n_v(mdist);
    end
    Power_risk=1-Power_risk;
    if flagplot==1
        disp(' ');
        for mdist=1:Mdist
            day_beg=sum(n_v(1:(mdist-1)))+1;
            day_end=sum(n_v(1:mdist));
            fprintf(1,'Power Risk for each of the days between %i and %i:
%6.3f%%\n',day_beg,day_end,100*Power_risk_v(mdist));
        end
        disp(' ');
        fprintf(1,'Mission Power Risk: %6.3f%%\n',100*Power_risk);
    end
end
```

```
>>PowerSupply=220;mu_swT_v=[ 6 ; 4 ; 3 ;6];sig_swT_v=[ 3; 4; 4.5 ;3];
>>mu_aT_v=[ -10; -12; -8; 5]; sig_aT_v=[ 5; 6 ; 6 ; 4.5];
>>cor_swT_aT_v=[ .5; .6;.4;.5]; c_v=[ 4; 5; 3; 2]; flagplot=1;

>>[Power_risk,Power_risk_v]…
=Risk_generalized_model(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupply…
,mu_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,c_v,flagplot)
```

```
Power Risk for each of the days between 1 and 4:  1.843%
Power Risk for each of the days between 5 and 9:  6.671%
Power Risk for each of the days between 10 and 12:  1.419%
Power Risk for each of the days between 13 and 14:  0.000%
```

Appendix E: Power Supply Risk Curve

```
function [Power_riskHa_v,Power_riskHs_v] =
PowerSupply_Risk_curve(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupplyH_v,Npr,mu
_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)
% PowerSupply_Risk_curve calculates and plots the Mission Power risk against the
hypothetical Power Supply in PowerSupplyH_v
%
%  [Power_riskHa_v,Power_riskHs_v] =
PowerSupply_Risk_curve(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupplyH_v,Npr,mu
_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,flagplot)

    % default values
    if nargin<12 || isempty(flagplot)
        flagplot=false;
    end
    if nargin<11 || isempty(n_v)
        n_v=[4; 5; 3; 2];
    end
    if nargin<10 || isempty(cor_swT_aT_v)
        cor_swT_aT_v=[.5; .6;.4;.5];
    end
    if nargin<9 || isempty(sig_aT_v)
        sig_aT_v=[5; 6 ; 6 ; 4.5];
    end
    if nargin<8 || isempty(mu_aT_v)
        mu_aT_v=[-10; -12; -8; 5];
    end
    if nargin<7 || isempty(sig_swT_v)
        sig_swT_v=[3; 4; 4.5 ;3];
    end
    if nargin<6 || isempty(mu_swT_v)
        mu_swT_v=[6 ; 4 ; 3 ;6];
    end
    % Units
    Power_Unit_str='kW';
    Lcurve=length(PowerSupplyH_v);
    Power_riskHa_v=NaN*PowerSupplyH_v;
    Power_riskHs_v=NaN*PowerSupplyH_v;
    for i=1:Lcurve
        PowerSupplyt=PowerSupplyH_v(i);

Power_riskHa_v(i)=Risk_generalized_model(SeawaterT_m,AirT_m,PowerDemand_total_m,Pow
erSupplyt,mu_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,0);

Power_riskHs_v(i)=Risk_simulate_eval_dist(SeawaterT_m,AirT_m,PowerDemand_total_m,Po
werSupplyt,Npr,mu_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,n_v,0);
    end
    % Type
    if flagplot==1
       clc;
       for i=1:Lcurve
           fprintf(1,'when the Power Supply is %.2f %s, then the Mission Power Risk
is %6.3f%% (analytically) or %6.3f%% (with %i pseudo-realities)\n'...

,PowerSupplyH_v(i),Power_Unit_str,100*Power_riskHa_v(i),100*Power_riskHs_v(i),Npr);
       end
    end
    % plot
    figure(1);
    close(1);
    figure(1);
    h_v=NaN(2,1);
    h_v(2)=plot(PowerSupplyH_v,Power_riskHs_v,'b-');
    hold on
    h_v(1)=plot(PowerSupplyH_v,Power_riskHa_v,'r-','LineWidth',2);
    xlabel_str=sprintf('Hypothetical Power Supply in %s',Power_Unit_str);
```

```
    xlabel(xlabel_str);
    ylabel_str=sprintf('Mission Power Risk in %%');
    ylabel(ylabel_str);
    title_str=sprintf('Mission Power Risk as a function of the Power Supply');
    title(title_str);
    legend2_str=sprintf('Simulational (%i pseudo-realities)',Npr);
    legend_str_c={'Analytical';legend2_str};
    legend(h_v,legend_str_c,'Location','NorthEast');
end
```

```
>> PowerSupplyH_v=[160:1:270];PowerSupply=220;mu_swT_v=[ 6 ; 4 ; 3 ;6];
>>sig_swT_v=[ 3; 4; 4.5 ;3];mu_aT_v=[ -10; -12; -8; 5]; sig_aT_v=[ 5; 6 ; 6 ; 4.5];
>>cor_swT_aT_v=[ .5; .6;.4;.5]; c_v=[ 4; 5; 3; 2]; Npr=1000; flagplot=1;
```

```
>>[Power_riskHa_v,Power_riskHs_v]…
=PowerSupply_Risk_curve(SeawaterT_m,AirT_m,PowerDemand_total_m,PowerSupplyH_v,Npr…
,mu_swT_v,sig_swT_v,mu_aT_v,sig_aT_v,cor_swT_aT_v,c_v,flagplot)
```

```
when the Power Supply is 160.00 kW, then the Mission Power Risk is 100.000% (analytically) or 100.000% (with 1000 pseudo-realities)
when the Power Supply is 161.00 kW, then the Mission Power Risk is 100.000% (analytically) or 100.000% (with 1000 pseudo-realities)
when the Power Supply is 162.00 kW, then the Mission Power Risk is 100.000% (analytically) or 100.000% (with 1000 pseudo-realities)
when the Power Supply is 163.00 kW, then the Mission Power Risk is 100.000% (analytically) or 100.000% (with 1000 pseudo-realities)
when the Power Supply is 164.00 kW, then the Mission Power Risk is 100.000% (analytically) or 100.000% (with 1000 pseudo-realities)
……………………………………………………………………
when the Power Supply is 268.00 kW, then the Mission Power Risk is -0.000% (analytically) or  0.000% (with 1000 pseudo-realities)
when the Power Supply is 269.00 kW, then the Mission Power Risk is -0.000% (analytically) or  0.000% (with 1000 pseudo-realities)
when the Power Supply is 270.00 kW, then the Mission Power Risk is -0.000% (analytically) or  0.000% (with 1000 pseudo-realities)
```